

WORLD METEOROLOGICAL ORGANIZATION

PROCEEDINGS
OF THE
**WORLD CLIMATE
CONFERENCE**

A CONFERENCE OF EXPERTS ON CLIMATE AND MANKIND

GENEVA, 12-23 FEBRUARY 1979

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FOREWORD

The Executive Committee of the World Meteorological Organization at its twenty-ninth session (May-June, 1977) decided that the Organization should convene a scientific and technical World Climate Conference to be held in February, 1979, in Geneva. The main purposes of this Conference were to be:

- (a) To review knowledge of climatic change and variability, due both to natural and anthropogenic causes; and
- (b) To assess possible future climatic changes and variability and their implications for human activities.

An Organizing Committee was formed comprising representatives from a number of international bodies and scientists in their individual capacities. Dr. Robert M. White was elected chairman. The Committee agreed that, in order to meet its objectives, the Conference should consist of two phases each lasting one week and the arrangements proceeded on this basis.

During the first week (12-16 February 1979) a number of invited speakers presented comprehensive and authoritative Overview Papers covering current knowledge of climate and the interactions between climate variability and change and human society. These were discussed at length by an assembly of some 350 participants from all parts of the world.

In the second week (18-23 February 1979) more than 120 invited experts representing many disciplines and regions of the globe drew upon the information presented in the first week and their own knowledge to assess the present understanding of climate and its interactions with mankind, and to formulate general recommendations for international action.

The deliberations of the second week of the Conference were largely organized to follow the structure of the emerging World Climate Programme which was to be submitted to the Eighth WMO Congress (May-June, 1979). The World Climate Programme as then planned and subsequently approved by Congress, consists of four closely related components:

- Climate Data;
- Applications of Knowledge of Climate;
- Study of the Impacts of Climate on Human Activities;
- Research on Climate Change and Variability.

The Conference noted that there was an additional issue of special importance that pervades all the above-mentioned components: The problem of possible human influences on climate. The invited experts who took part in the second week were therefore organized into working groups dealing with the four components of the World Climate Programme and the problem of human influences on climate.

A very important outcome of the Conference was the adoption of "The Declaration of the World Climate Conference" which has already been given wide distribution by WMO. The results of the work of the above-mentioned groups were drawn up in the form of Supporting Documents to the Declaration of the Conference and may be considered a summary of the views of the Conference as a whole.

This present volume is entitled "Proceedings of the Conference". It contains:

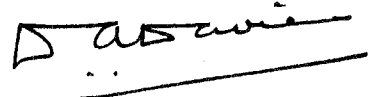
- (a) The complete texts of the overview papers presented;
- (b) The summary of discussions which took place during the first week;
- (c) The text of "The Declaration of the World Climate Conference";
- (d) The Supporting Documents to the Declaration of the World Climate Conference.

I wish to take this opportunity of expressing the gratitude of WMO to the many persons and organizations who made this publication possible. The Organizing Committee under the brilliant chairmanship of Dr. White played an outstanding role in all phases of the project while the authors of the overview papers are also to be thanked and congratulated on their outstanding contributions. Indeed all participants at the Conference, in their respective ways, contributed to its undoubted success.

As already mentioned above the Conference was a joint effort by WMO and other United Nations Agencies such as the United Nations Environment Programme (UNEP), the Food and Agriculture Organization (FAO), the United Nations Educational, Scientific and Cultural Organization (Unesco), and the World Health Organization (WHO). Special mention should be made of the assistance provided by the International Institute for Applied Systems Analysis in hosting the preliminary review session of the Overview Speakers at its Headquarters in Laxenburg in April 1978. The co-operation of these organizations contributed a great deal to the success of the Conference.

This publication may safely be considered as the most profound and comprehensive review of climate and of climate in relation to mankind yet published. As a major input into the deliberations of the Eighth WMO Congress, the Conference has already contributed greatly to the World Climate Programme now approved for implementation. In a wider context it is believed that the Conference has contributed greatly to a better understanding of the overall problems of climate and to finding solutions to these problems.

The publication of the Proceedings of the Conference in this present form will ensure a very wide dissemination of the knowledge, views and judgments it contains and will thereby facilitate a full discussion of many issues of great importance to the future of our world society.

A handwritten signature in dark ink, appearing to read "D.A. Davies", written over a horizontal line.

D.A. Davies
Secretary-General

PREFACE

The World Climate Conference was convened during the period 12-23 February 1979 at the request of the Executive Committee of the World Meteorological Organization. Scientists and other specialists from fifty different countries representing many scientific and other disciplines attended the Conference to assess the present state of knowledge about climate and to examine the nature of the impact of climate upon society. A list of the participants in the Conference is presented in Appendix B to this report. Those whose names have asterisks represent the invited experts who also participated during the second week of the Conference.

The Declaration of the Conference appearing in these Proceedings was prepared and unanimously adopted during the second week of the Conference. This Declaration was based upon the Supporting Documents prepared by working groups of invited experts, and these are also reproduced in this volume.

The assessment of our present state of knowledge about climate is represented by the Overview Papers which comprise the main body of these Proceedings. They describe the present status of our scientific knowledge of climate and its variability, as well as of the impacts of climate upon society. The presentation of the Overview Papers was accompanied by extended discussions among the participants and the Overview Speakers. A summary of the highlights of these discussions is presented at the end of the overview section.

The programme of the Conference is presented in Appendix A and identifies the Overview Speakers, the titles of their papers, and the Chairmen and Co-chairmen of the various sessions and working groups. I wish to extend special appreciation to Dr. Robert W. Kates who, at the request of the Bureau of the Organizing Committee, prepared a paper at very short notice which provides a framework for some interdisciplinary approaches to many different problems of climate.

The Overview Papers, the Declaration, the Supporting Documents, and the Session Summaries were prepared and edited through the efforts of many people in addition to the authors. Dr. F. Kenneth Hare, Director of the Institute for Environmental Studies of the University of Toronto, Canada, acted as the principal editor of the Overview Papers in collaboration with Mr. Patrick J. Meade, British Meteorological Office (retired), and Dr. William W. Kellogg, consultant to the Secretary-General of the World Meteorological Organization. Assisting in the preparation of the documentation for the Conference were Dr. T.E. Munn of the Institute for Environmental Studies of the University of Toronto, Canada; Dr. Ilya Polyak, Main Geophysical Observatory, Leningrad, USSR; Dr. John S. Perry and Mr. Jesse Ausubel, U.S. National Academy of Sciences; and Dr. Victor Boldirev, State Committee for Hydrometeorology and Control of Natural Environment, USSR.

The preparation of these Proceedings of the World Climate Conference could not have been possible without the outstanding support of the Secretary-General and members of the staff of WMO. Special note must be taken of the assistance rendered by Dr. H.A. Taba, Director of the Office of Programme Planning and U.N. Affairs, and Mrs. J. Stickings, Administrative Assistant.

Robert M. White
Chairman
World Climate Conference.

CLIMATE AT THE MILLENNIUM

by

Robert M. White*

Chairman

World Climate Conference

Keynote Address

* U.S. National Academy of Sciences, Washington, D.C., U.S.A.

Mr. President, Mr. Secretary-General, distinguished participants: The World Climate Conference has been convened to assess the state of man's knowledge of climate and to consider the effects of climate variability and change on human society. The issues we will address during the next two weeks are as old as mankind and as new as our interdependent social and economic systems. During this Conference we will hear how climate has shaped our past, moulds our society today, and may affect our future. We can learn from the past, endure the present, but the future is in our hands. We can contribute to a bright future for mankind by national and international actions to provide for the wise use of climatic resources to improve the economic and environmental welfare of people everywhere and to mitigate destructive impacts of climate. This conference can be the beginning of that process.

One may ask, "Why a World Climate Conference now?" The timing of our meeting is a response to several concerns. The first is the worldwide reaction to the climatic events that have so disrupted human society over the past decade. The second arises from a growing appreciation that not only is humanity vulnerable to variations in climate, but climate is also vulnerable to the acts of humanity. The third is a perception of a broader climatic vulnerability stemming from world population growth, increased world demand for food, energy, and other resources, increased interdependence of nations, and the pace of economic development. It is a vulnerability that can only increase because the underlying causes will intensify, not diminish.

The disastrous consequences of climatic events of the past decade are well known. No part of the world has been immune. During the late sixties and early seventies the southern border regions of the Sahara desert, the Sahel, succumbed to a five-year drought with famine and death on a continental scale. The year 1972 saw a worldwide epidemic of costly climatic episodes, including drought in the Soviet Union and the occurrence of El Niño off Peru. In 1974, poor monsoons reduced food production in India. In 1975, cold waves in Brazil badly damaged coffee crops. In 1976, drought in Europe caused widespread economic dislocation. In the United States, the recent cold winters forced many industries and schools to close.

These events have demonstrated the sensitivity of human welfare and international relations to climatic events. They have demonstrated the fragility of world food production and trade systems and the extent to which income and employment continue to depend on the workings of the natural world. The remarkable aspect of these climatic fluctuations is that they are not unusual. Similar events have occurred frequently in the historical record. What is new, is the realization that vulnerability of human society to climatic events has not disappeared with technological development.

Moreover, we cannot allow shorter period fluctuations of climate to lull us into complacency. We have been blessed by a benign climate in most of the world during the past several years, save for parts of the Sahel in the past year. As a result there has been a lessening of attention in the public press and among governmental officials in their concerns about climate.

To connect human suffering exclusively to natural events is utterly mistaken because the vulnerability or resilience of a society to climate obviously depends on many factors. To illustrate, it is interesting to observe that during the decade of the seventies the world grain trade went through one full cycle of surplus to shortage and back to surplus. In the early 1970's, there were large world grain reserves. During the period 1972 - 1974 world food production on a per-capita basis suffered its sharpest decline in twenty years. Crop failures due to climatic stress occurred in many parts of the world. We then reached a stage in which the stocks of grain, on a worldwide basis, had been reduced from a normal 20 per cent of world consumption to about 10 per cent. But, by 1977 and 1978, global grain harvests were setting records. With such fluctuations in the world food grain picture, it is easy for decision-makers to forget the disaster of yesterday and remember only the good times of today. As climate specialists, we know better.

If natural climate disasters had not been enough to motivate governments and the scientific community to action, the ominous possibilities for man-induced climatic changes would have triggered our presence here. Until the beginning of the industrial age some 100 years ago, variations in climate and their associated impacts could be considered as natural events beyond the control of man. In recent years, we have come to appreciate that the activities of humanity can and do affect climate. We now change the radiative processes of the atmosphere and perhaps its circulation by emission of the products of our industrial and agricultural society. We now change the boundary processes between earth and atmosphere by our use of the land.

We are only dimly beginning to understand some of the potential consequences of human impacts on the climatic resources of the world. However, it is difficult to remain complacent. The potential consequences of increasing atmospheric carbon dioxide resulting from fossil fuel combustion are already a major world concern. But evidence continues to accumulate that the growth of human habitations and the consequent destruction of forests reduces the terrestrial reservoir of carbon and further increases airborne carbon dioxide. Recent findings that other gases reinforce and amplify the effects of carbon dioxide further intensify this concern. It is hard to be complacent when we know that the population of the world will need increasingly to turn to nitrogen fertilizers to maintain agricultural production with the potential for releasing nitrogen compounds which can alter the photochemical balance of the stratospheric ozone. The potential effect on stratospheric ozone of the oxides of nitrogen released in supersonic flight, and of chlorofluoromethanes (CFMs) used as refrigerants or propellants also raise the issue of human impact upon climate.

Moreover, it is the future course of these trends that must be a central concern of this Conference. In little more than twenty years, we will celebrate the year 2000. This millennium may very well represent the ending of one era in the relation of humanity to the planet and the beginning of another. The millennium may mark a fundamental change in the ability of the planet to sustain its people or at least in the ways in which this will be done. There are many who will disagree with the timing of this fundamental change but few who will disagree with its likelihood. By any criteria, whether relating to population, food, energy, or the state of the global environment, we are likely to pass to a new world condition around the year 2000. This transition will also signal a new level of importance of climate to society.

Let us look at what the millennium holds. Conservative projections indicate that the population of the world, which in 1970 was approximately 3.5 billion, will increase to approximately 6.5 billion by the year 2000. Projections made by the United Nation's Food and Agriculture Organization indicate that, as a result, world aggregate food demand will rise by about 44 per cent by 1985 and 112 per cent by the year 2000 - a doubling by the millennium. The challenge facing the world to increase its food production by this amount is staggering. Some surveys of additional land and water potential for agricultural expansion indicate that the developing areas of the world (except in Asia) possess abundant underused land and water resources with great agricultural potential. This view is not universally accepted, however. While it will be costly to bring these virgin land and water resources into production, it can be done if the best in technology and science is brought to bear.

Beyond the year 2000, the world will face a different food situation. We will need to move beyond bringing virgin lands into agricultural production. Agricultural scientists will have to look to new strains of crops, crops that can be grown in brackish or salt water, multiple cropping, and other new approaches to meet the situation. However, projections of world food demand and supply indicate a continuing and growing imbalance. In the next twenty years, climatic information and services derived from strengthened climate data bases in the developing world will be particularly critical to assure the necessary agricultural productivity. Eventually, perhaps by the year 2000, it will become necessary to advise on how agricultural lands of the entire globe and their characteristic climates can be used in an optimum fashion to maximize the world production of food and fibre. We must therefore begin to think of climate itself as a resource to be allocated wisely.

By the millennium, the world energy situation will be no less ominous. Estimates are that by the year 2000 the desire of the world for oil will have far surpassed world oil production, even with a 50 per cent increase in oil prices. In seeking to meet our energy needs we may pose a threat to global climate with formidable consequences for world society. In the next twenty years, we will see both the introduction of new sources of energy and a growing dependence on coal and nuclear power.

The growing dependence of the world on coal may create the most serious threat to the world's climate. By the addition of carbon dioxide to the atmosphere, we change its fundamental temperature controls. It is estimated that the burning of fossil fuels and destruction of forests - also, incidentally, a source of fuel - have already, in the short span of one half century, increased atmospheric carbon dioxide content over 10 per cent. The implications of further projected increases are uncertain, but the weight of scientific evidence predicts a significant global surface temperature increase. Other energy sources also have important climatic implications. The increasing use of renewable forms of energy derived from the sun, the wind, and the ocean will call for a new level of climatic services and present a new set of challenges to climate science.

As with food, we will need credible projections of consequences by the millennium, if energy policies are to be modified in time to avoid adverse climatic impacts. The implications of the world food and energy outlooks for our science are

clear - we have no time to lose. The complex interplay between climate and man and the environment, as exemplified by food and energy, forces us to realize the degree to which climate is a key element in a global ecological system involving the atmosphere, the oceans, cryosphere, the solid earth and the biosphere. Because no social system, or economic condition of development, renders nations impervious to the physical processes of nature, and because in the modern world environment we are so dependent on one another, it is essential that we join together to consider what we can do collectively and individually about climatic issues in the interest of all.

At the same time, this Conference must take a long view. It must bring to the attention of governments the fact that the problems we are dealing with will not be solved in a day, a year, or even a decade. They are problems for all time and we must address them with fresh concepts.

One important new concept that arises from the material prepared for this Conference is that we should begin to think of climate as a resource. Climate does not conform to our normal idea of a resource. However, its variability in time and space does, in fact, confer upon it many of the characteristics of a resource. For example, on a small scale, farmers and communities located no more than a few kilometres apart may enjoy remarkably different climate assets. The slopes of the Rhine Valley produce fine white wines at northerly latitudes normally hostile to such production. Tea is produced in Soviet Georgia, and the citrus groves along the Mediterranean shores of Egypt enjoy the benefits of the Mediterranean moisture which only a few kilometres inland is non-existent.

Furthermore, while access to climatic resources is restricted by national boundaries and property rights, climate also has some of the characteristics of a common property resource because it can be modified by the remote actions of man. It is the common aspect of the climate resource that will raise the most difficult issues for governments and humanity. For example, while the consequences of a global warming can only be speculated at this time, it is clear that such a change would have vastly different impacts in various regions of the world. There would be winners, and there would be losers. A climate change could be the cause of a major redistribution of wealth, and from the point of view of mankind, quite an arbitrary one.

The possibility that actions by individual nations may influence the climates of others may demand new types of international action. Accords have already been reached in the United Nations to prevent the deliberate use of potential techniques of climate modification as instruments of warfare. However, nations can still proceed unilaterally with a variety of projects in energy, land use, or water resource development that may conceivably affect climate beyond their borders. We thus see emerging a need for some mechanism to develop global environmental impact assessments that will be accepted by all nations. Thus, for certain purposes we must put climate alongside such global commons as the deep seabed and outer space as a concern of mankind for which new international obligations must be derived. Let us hope that this Conference marks the commencement of a new level of collaboration for the protection and productive use of climatic resources.

International concern about the future global condition has been manifest in the remarkable series of World Conferences convened by the United Nations during the past decade. The United Nations Conference on Environment in 1972 in Stockholm was the first occasion on which the world confronted common problems of global concern whose solution could be achieved only by the closest collaboration among nations. Even at this first World Conference, climate impacts were central concerns. Indeed, understanding climatic fluctuations and their impacts became one of the high priority action items. As a result, the United Nations Environment Programme, which resulted from this Conference, has maintained a strong interest in climate. Two years later, in 1974, the United Nations World Food Conference recognized the central role of climate in world food production and the need for improved understanding of climatic fluctuations by calling upon the World Meteorological Organization and the Food and Agriculture Organization to establish a climate warning system. In 1976 the United Nations convened a World Water Conference at Mar Del Plata in Argentina. That Conference emphasized the importance of understanding climatic variations and their effects upon water supplies and usage throughout the world. Most recently, at the United Nations Conference on Desertification, the nations unanimously adopted resolutions emphasizing the need to understand climate and the United Nations Economic and Social Council adopted a resolution endorsing the World Meteorological Organization initiation of a World Climate Programme.

The importance of climate, recognized in these Conferences, suggests that the time is at hand to view world affairs through a climatic prism. This is what we will do at this World Conference. We will recognize the central role of climatic processes in the shaping of the world's economic and environmental welfare, its political stability, and even world peace.

The challenge to our science is unprecedented. Indeed, it is a challenge to all of science because the problems we must confront are not strictly meteorological, although they have a high meteorological content. The scientific problems that must be solved involve complex environmental and ecological systems. What other problems of global concern invoke a knowledge of the photochemistry of the upper atmosphere as well as the chemistry of the depths of the ocean? What other problems engage our knowledge of astronomy and solar physics, at the same time as they invoke our knowledge of the geophysical and geological structures of the earth and the seabed? What other problems require a knowledge of the interrelation between the processes of the biosphere as they are impacted by human settlements and their effects on the chemical composition of the atmosphere? What other problems engage us in the science of the radiative properties of gases and the dynamics of geophysical fluids? How many scientific problems have the potential for shaping the economy of nations and disrupting the economic and political relations among them?

Thus, this Conference must represent diverse disciplines. We need to be not only atmospheric scientists but geologists and oceanographers and geophysicists. And we need those who are expert in the fields of agriculture, land use, energy, and water resources, those who are knowledgeable about health and fisheries and marine transport, and economists, geographers and sociologists to assist us in the documentation of the nature of climatic impacts. And because climate is a global problem, it is so important that representation comes from all over the world, from countries with different economic and social systems. We believe this "Conference of Experts

on Climate and Mankind" has brought together the diversity of experts who can address the complex issues before us.

To commence the Conference, a number of overview papers have been commissioned by the World Meteorological Organization in association with the other United Nations agencies. These outstanding papers offer assessments of the state of our knowledge and raise the issues we should discuss. We will hear presentations of these papers during the first week of this Conference. They will provide the framework for the Conference as a whole. During the second week, groups of invited experts have been asked to remain to prepare the detailed findings and recommendations of the Conference. This will be a representative group of experts from diverse scientific and technical fields and regions of the world.

The findings and recommendations of this Conference will have a broad impact throughout the world. They will be transmitted to the Congress of the World Meteorological Organization which will be held in this city two months from now, to serve as a basis for decisions by governments on the scope of a new World Climate Programme. They will also be transmitted to other United Nations agencies, to non-governmental international groups, and to governments.

One potential recommendation is especially important. The Executive Committee of the WMO has specifically asked this Conference to recommend whether a conference at the ministerial level should be convened to take necessary international actions. It is not surprising that, with the uncertainty surrounding questions of climate, governments and others look for guidance. It is important that we inform governments of the best scientific opinion about the future global climate. Even an answer that science is not able with any reliability to foretell the future will be valuable. However, if our assessment is such that we believe there is a high probability of significant change, we should consider recommending broader actions at international political levels.

It is through the World Climate Programme, a programme sponsored by the WMO, and other international governmental and non-governmental bodies, that the recommendations of this Conference will be most readily and directly translated into programmes of international action. It is important, therefore, to understand the emerging shape of this World Climate Programme because it will set the context within which our deliberations can be most fruitful. The World Climate Programme will be a programme of international action addressing the full range of climatic issues that confront mankind. The World Climate Programme will mount three major interacting streams of international effort.

The first of these will seek to attack the problems of climate science. Through this effort we will seek to improve our understanding of climate change and variability and improve our ability to predict the natural variations in climate and the consequences of man's effects. This research effort will build upon the remarkable achievements of the Global Atmospheric Research Programme launched a decade and a half ago to examine the possibilities of extending the time range of weather forecasts and to achieve an understanding of the dynamics of climate. The Global Atmospheric Research Programme was set in motion in response to the new global observational capabilities of earth-orbiting satellites at the beginning of the space age, and will culminate this year in the most comprehensive international scientific

experiment ever conducted. This experiment, known as the Global Weather Experiment, will see the international deployment of five geostationary and two polar-orbiting satellites, all in simultaneous orbits. It will involve fleets of aircraft to explore the tropical atmosphere and an armada of over forty ships and networks of automatic data buoys distributed throughout the northern and southern oceans to probe the seas. A unique global meteorological data base should result, which can serve as a focus for the study of seasonal and interannual variations in climate.

The second stream of activity of the World Climate Programme will provide a new level of climate data and applications throughout the world. This international effort will seek to improve the climatic services principally in developing nations. Development planning for agriculture, energy, water resources management, human settlement and land use could be markedly improved by more effective use of climatic information. Even the simplest climatic observations are lacking in many parts of the world. Fortunately, this situation is remediable through national and international actions to provide necessary education, training, and technical assistance.

The third stream of activity addresses the need to understand the impacts of climate variability and change upon society. We all appreciate the direct effects of drought upon crops, or cold winters upon energy demand. What we do not understand clearly, and what governments are concerned about, is the question of the integrated impact of climatic change and variability upon society. Climatic events are but one element in complex worldwide, regional, and national economic structures. We wish to learn how the chain of interactions that may ultimately result in malnutrition or unemployment or other critical situations is dependent upon climate. Why are some social and economic structures more resilient to climatic events than others? Do these differences depend on factors we can do something about? If so, what can be done about them? The examination of these impacts is the major objective of this Conference.

You may ask, "Why should the climate community extend its concerns so far beyond scientific and technical matters into the realm of economics and social structure?" The answer is clear: Our task is to identify not just what it is that science should do, but what it is that governments should know. Unless there is a better comprehension of the chain of events and the complex interactions that take place, governmental decisions to mitigate the economic, social, and other effects of climatic impacts may very well provide the wrong remedies.

This gathering should be able to advance our understanding of many of these problems. At this meeting we have an opportunity for extensive discussion between scientists and those knowledgeable about economics, industry, agriculture and governmental practice. The uniqueness of this opportunity has been recognized by the World Meteorological Organization, whose Executive Committee has made a special request to this Conference to review and approve an International Plan-of-Action for the study of the impacts of climate upon society. This Conference has before it a draft Plan-of-Action prepared under the aegis of the Conference Organizing Committee for its review, consideration, and transmittal to the Congress of the World Meteorological Organization.

Ultimately, what we do about climate issues depends upon the state of our scientific knowledge. Only to the extent that we have understanding can we help our governments. Governments wish to know where to focus effort and resources. The international resources that can be made available to deal with climatic problems are limited. This is so not merely because finances are limited, but because the number of scientists capable of working effectively on these problems is limited. Because of this, efforts must be focused on those climatic problems where there is an urgent need for answers, and where the state of our scientific knowledge leads us to believe that it may be possible for science to make a useful contribution. Mere assertions that the socio-economic impacts of climate will be severe will not be accepted by governments confronted with many urgent requests for resources for programmes all directed at improving socio-economic conditions. It is incumbent upon us not just to assert, but to make the case for international investments in climate research and services.

Thus, the challenge is before us. Our governments will weigh the importance of investments in climate problems in terms of economic and social consequences. As scientists we must weigh what we choose and propose to do on the basis of our assessment of whether science can help. This presents us with a dilemma. We must not raise expectations beyond the scientifically reasonable nor raise fears beyond those scientifically warranted. But it is equally our responsibility to ensure that the possible consequences of either natural or man-induced climatic variations and changes are fully appreciated and the potential of science to assist clearly stated.

Our task is to present the essence of our knowledge and our expectations. If this Conference can allay rather than raise fears, it will have achieved much. If, on the other hand, we find it necessary to alert the world to the need for international action, we cannot shirk that responsibility. Our charge is clear, our responsibility great, our task complex. I am confident that this Conference will meet its obligations.

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OVERVIEW PAPERS

CLIMATIC CHANGE AND HUMAN STRATEGY

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1. Introduction

In recent years both the scientific community and the general public have been increasingly concerned about the possibility that irreversible changes may be taking place in the natural environment, especially in regard to climatic change. Is there any scientific basis for such concern about our climate, in a period when scientific and technological progress seems to be making mankind less constrained by the natural environment and, in particular, less vulnerable to unexpected climatic events?

The construction industry, once highly seasonal, is now active all the year round. We can reclaim deserts for agriculture, and can apply urban technology so as to create large and comfortable communities in the Arctic. Despite these and other developments, however, our contemporary way of life requires much more careful and detailed understanding of, and adjustment to, climate and the other elements of the natural environment if a reasonable balance is to be achieved.

The present scale of human activity, as measured both by its size - the magnitude of construction, the fraction of the earth's surface transformed, the amount of mineral resources extracted, the quantity of energy that is developed and utilized, the effects of human activities on the composition of the atmosphere and hydrosphere - and by the duration over which it has taken place, has increased so much that it has become comparable with naturally occurring phenomena.

In such circumstances any mistakes that we make in our assessment of the present and future states of both the natural and the transformed environments (e.g., in our estimates of mineral resources, average and extreme values of river discharge, precipitation, sea-level, etc.) are liable to lead to very large cumulative errors. If we provide unnecessary safety margins, of strength, size or power, this is very expensive. If, however, our margins are inadequate, the results may be disastrous.

On the other hand, inadvertant impact on the environment leads to various problems in the development of human activity. Uncontrolled transformation of the natural environment has already led to increasingly adverse consequences.

Climate is a particularly significant element in such considerations, since practically all forms of economic development must take it into account, and because many forms of human activity have some effect on climate.

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It is for these principal reasons that the question of natural or man-induced climatic change is of such importance. The present paper provides a brief summary of natural and induced climatic changes (both spontaneous and deliberate), describes the impact of such changes on economic and social activity and discusses the strategy, much of it long-term, which mankind should adopt in order to avoid the undesirable effects of such changes.

Before discussing changes of climate, however, it is desirable that we should define the concept of climate itself. In our view, it is both a consequence and a demonstration of the workings of complex processes in the atmosphere, the oceans and on land. These processes cause changes in the climate system. Some of the changes are random, others are systematic, e.g., the cycle of the seasons year by year. Nevertheless, the main features of the climate, when averaged over a substantial period of time (i.e., years or decades) do exhibit stability in all parts of our planet

Nowadays, there is no general agreement on the appropriate period over which climatic data should be generalized. The most common view, with which we agree, is that a period of 10 to 30 years is suitable, although other views will be presented at the Conference.

2. Climatic change resulting from natural causes

The results of geological, archaeological and historical investigations all indicate that radical changes of climate have taken place throughout the Earth's history. It is difficult, however, to say much that is meaningful about the climate of any specific geographical region in the remote past because of continental drift and polar wandering; in other words, any specific region of the planet has not necessarily remained in its present latitudinal or longitudinal position throughout geological time. There is, however, good reason to believe that during the last several hundred million years, the normal climate of the Earth as a whole was much more homogeneous than it is at present; there were not the pronounced differences in climate between different latitudes that we have today.

Several tens of millions of years ago, this situation began to change and the temperatures of high latitudes fell gradually. About two million years ago this process accelerated, and Arctic temperatures dropped sharply. A glacial period ensued in which repeated advances of ice sometimes reached mid-latitudes, with intervening periods when the ice receded.

Since that time, less marked climatic changes have taken place. For example, approximately one thousand years ago the temperature of the north polar region was higher than it is today, and the limit of sea-ice was further north than it is at present.

The same fall of temperature was experienced in the northern hemisphere, where it is often described as a "neoboreal" period, or "Little Ice Age". More recently still, climatic changes have also occurred during the last 100-200 years, and temperature changes during that time have been particularly marked in high latitudes. The best-known example of such recent changes is the warming of the Arctic that reached a peak in the 1930s.

Temperature, however, is not the only indicator of climatic change; precipitation amounts also vary. For example, variations in the winter precipitation in the North European part of the U.S.S.R. have caused changes in the level of the Caspian Sea. During the last four or five hundred years there have been several rises and falls in this level, with a range of about 20 m to 25 m.

There are a number of hypotheses that try to account for climatic change. Many of them are to be presented at the Conference but as yet there is no adequate physical theory capable of providing a comprehensive explanation of the observed phenomena.

It is important to note that, during the last few thousand years, climatic change has occurred during a period when the Earth's orbit and its surface structure (location of continents and oceans, mountain ranges, etc.) have been relatively constant, and when it is probable that the nature and quantity of solar radiation were also constant. This leads to the belief that on the Earth as it is at present there is not one but several equilibrium states of the whole complex of hydrometeorological processes in the atmosphere and oceans, i.e., not one but several possible patterns of world climate. It seems reasonable to conclude also that a change from one of these patterns to another may be caused by relatively insignificant factors. Indeed the complex interactions between the various processes of climate, including feedbacks, make it possible that in some cases the changes are generated or triggered by the climatic system itself. Calculations made by M.I. Budyko [1], one of the leading Soviet climatologists, indicate that the present climatic pattern of the Earth, and patterns similar to it, are generally unstable. In his view there are only two inherently stable patterns: the uniformly warm climatic pattern over the Earth and a complete glaciation of the Earth.

It is not the purpose of this paper, however, to analyse or evaluate the various hypotheses. It seems more important for our present purpose to emphasize the fact that, throughout the history of our planet, the climate has been liable to change in response to natural factors or causes, and consequently there is no reason to suppose that similar changes are unlikely in the future. In recent years, in both scientific and popular literature, many papers have appeared that describe a supposed fall in temperature in the northern hemisphere during the 1960s and 1970s; this fall is supposed to have been both widespread and relatively rapid. It has been attributed to restructuring of the general circulation of the atmosphere, to significant changes in the distribution of rainfall and to a variety of other causes. It seems worth mentioning at this point that detailed investigations by many scientists, and especially by a large team of Soviet scientists, have found such apprehensions to be groundless, though very small cooling (about 0.5 deg C) is taking place in the northern hemisphere. More probably, in the coming decades it seems reasonable to anticipate small climatic changes similar to those that are known to have taken place during the last 100-200 years. In particular it seems very probable that a warming trend is just beginning in the northern hemisphere; as during the 1930s, this is likely to be most pronounced in the Arctic.

3. Climatic changes induced by human activity

Human existence, like the existence of other living beings, necessarily has its effects on nature. Human development could not have taken place as it has without

simultaneously transforming different elements of the natural environment. In our view, the impacts that are of the most relevance to the subject of climatic change are the following:

- (a) The transformation of the land surface of the planet by forest clearance, the ploughing up of the steppes and great plains, land reclamation, etc.
- (b) Changes in the water balance, as an increasing proportion of river discharge is used for irrigation or to meet industrial needs. Evaporation over land areas consequently tends to increase and runoff into the oceans decreases. This will not change the general hydrological cycle on the planet, but it will lead to a different relationship between the various elements of the cycle in different geographical regions. Evaporation, condensation and freezing of moisture are also, it should be noted, significant elements in the energy balance of the atmosphere.
- (c) Changes in the energy balance. The earth-atmosphere heat balance can be changed both by alterations in the transparency of the atmosphere and by direct release of sensible heat as a result of power generation and the use of all types of energy.

Most of those who have investigated the problem believe that at present one of the principal effects of man on climate occurs through carbon dioxide emissions resulting from the burning of fossil fuels. These emissions lead to a worldwide increase in the CO₂ content in the atmosphere, enhancing the so-called greenhouse effect. Budyko [1], Bolin [2], Baes, Goeller, Olson and Rotty [3], Flohn [4] and many others suggest that the continuation of current rates of growth in energy use based on fossil fuel will lead to a substantial percentage increase in the atmospheric CO₂ concentration during the next 50 to 100 years, and that this in turn will raise the temperature of the atmosphere and lead to significant climatic changes.

One frequently sees, in scientific as well as popular literature, the belief expressed that such increases in CO₂ concentration (and also direct release of sensible heat) will result in a more or less uniform rise in temperature in the lower atmosphere. This in turn is presumed to lead to global warming, melting of glaciers, etc. This view seems oversimplified. Increases in temperature are likely to be most pronounced in the Arctic, and consequently the temperature gradient between Equator and polar regions would diminish. This implies changes in the general circulation of the atmosphere, reducing, for example, the west-to-east flow of moist air from the Atlantic Ocean over Eurasia, Europe, etc. We cannot in fact estimate the character and magnitude of such changes, and the climatic pattern that would result from them in different parts of the world.

Climatic variations, however, can be the result not merely of changes in the global heat balance but also of the geographical redistribution of the elements of the heat balance, including the sources and sinks of heat and their relative growth or decline. This in turn raises the important question whether the known effect of existing major heat sources on local climate could, if such sources grew in magnitude, become evident also at the regional or global scales. It is well known that the air temperature in large cities is higher by about 2 to 4 deg C than in their vicinities.

Häfele et al. [5], for example, have examined the probable effects resulting from the construction of two large centres of energy conversion (e.g., thermonuclear complexes), one located close to the coast of the British Isles, the other in the western Pacific offshore from Canton. The authors found that changes in the atmospheric circulation would result in the form of latitudinal shifts in precipitation belts.

Many other papers have appeared recently that contain estimates of the additional heat required to alter the circulation of the atmosphere on a regional or global scale. Most of these estimates suggest that regional changes, at least, in the general circulation of the atmosphere can be expected if human activity were to add approximately 1-2 per cent of the heat at present absorbed by the Earth from the sun or if heat were released which led to a temperature rise of several degrees over an area of about one million square kilometres. These and other calculations focus on the growth in human energy use, but it is obvious that other forms of environmental change caused by human activity will also have climatic effects.

4. Deliberate modification of climate

If we accept that man has in the past been able to alter the climate without intending to do so, then in principle it should be possible to achieve similar changes deliberately. To do this we would require a quantitative theory of climate, in order to design actions on a scale necessary to achieve the desired changes. The development of such a quantitative theory does not appear to be an insuperable scientific task. For example, it seems reasonable to believe that the climate could be changed by a redistribution of the sources and sinks of heat over the Earth's surface as a result of constructing major centres for generating and using energy in specific locations.

It also seems possible to change the albedo over large parts of the world, again affecting the heat balance. Another approach might attempt to decrease the transparency of the atmosphere to solar radiation by substantially increasing the aerosol content of the upper layers. Independent calculations by different scientists indicate that it would be possible to alter the albedo of large areas of the polar regions and also to change the aerosol content of the upper atmosphere if a substantial number of aircraft could be made available for the necessary period for such a project. It does, however, seem rather irrational to reduce the amount of solar radiation reaching the Earth's surface in order to balance the growth of anthropogenic production of energy.

A rather different approach to climate modification is through interference with the dynamics of the atmosphere or the oceans. Similarly in the oceans, we know that spontaneous deviations of ocean currents from their normal track cause significant changes in weather. More permanent diversions of flow could be made to occur through the construction of specially designed barriers. They would be thousands of times larger than typical present-day dams, but in principle their construction is feasible.

Because the processes that combine to produce world climate are at present probably inherently unstable, it seems reasonable to assume that specific, once-only, actions could produce irreversible changes, in the circulation. Thus, for example,

according to the work of a number of scientists, if the ice cover of the Arctic Ocean were made to disappear, the atmospheric and oceanic circulations would adjust in such a way that the ice would not be able to re-establish itself. This in turn would lead to considerable changes of climate throughout the world.

Both the evidence for unintentional climatic change already occurring, and the possibility of deliberate modification of climate by man, require that as a matter of urgency we should find out what are the critical values of different meteorological parameters, in order to avoid such irreversible changes.

Social and political issues of some significance arise if we consider the possibility of climatic changes occurring in one part of the globe as a result of actions taken in another region. The question may be posed as follows: might an individual country, through actions taken on its own territory, be able to affect the climate of another country in a different part of the world? I believe that this is scarcely possible. Changes of climate (as distinct from weather) on a global scale are likely to require the activities of many countries in different parts of the world.

There are, however, other views on this subject. It may be recalled that, twenty years ago, the well-known American physicist Edward Teller thought it possible to modify climates for military purposes 6. We would like to draw attention to another very important side of this problem. Military operations, as is evident from the experience gained, have significant and always negative impacts on the environment and, in particular, on local climates. World thermonuclear conflict would undoubtedly result in significant degradation of the natural environment and climate of the whole Earth.

In this connexion, the proposal made by my own country in 1972 that changes to the natural environment for military purposes should be prohibited by international agreement was very timely. This agreement, which has already been ratified by many countries, must command the support of earth scientists.

In summary, it seems reasonable to anticipate that, in the future, world climate may be modified by deliberate human action. It may well be that such action will seek not to transform our present climatic pattern but rather to stabilise it, since the social and economic life of mankind is adapted to the present climate.

5. The effects of climatic change on man

Climate, and climatic changes, have always significantly influenced mankind, and they continue to do so at present. There is general agreement on this, although there are differing views on the precise nature of such influences.

Gerasimov (see his overview paper) considers that climatic changes during the geological past were the principal factors which determined the character and, in particular, the rate of development of our ancestors.

The well-known American geographer Huntington believed that the natural environment, and especially climate, determined all the features of economic,

technological and cultural life, and that even the social systems of human society reflected this environmental influence. Similar views are expressed at our Conference by Dr. White 7 who emphasized the influence of climate processes on the development and welfare of mankind and on the natural environment.

However, such views do not apply universally. Examples can be given of differences in welfare of people living in the same climatic conditions but at different levels of economic development. The progress achieved in social and economical fields allows some people to obtain a higher standard of welfare than their neighbours in the same climatic zones. Impact of climatic changes on various fields of economy is to be carefully reviewed at the Conference.

In addition to what was said at the beginning of this paper about the increasing responsiveness of modern civilization to environmental factors, it should also be kept in mind that scientific and technological progress allow us to live and work in increasingly extreme environmental conditions. Population growth and production and consumption increases force us to do so. In such circumstances, even quite small changes in the natural environment may have far-reaching consequences. For example, if a small part of the discharge of a major river is abstracted for the irrigation of agricultural land, the resulting reduction in its flow, say by 15-20 per cent (which is quite feasible), would probably have no major ill effects. However, if all or almost all the discharge is abstracted, then such reduction in flow may cause a marked fall in the food production of a large region. Our ancestors had fewer possibilities but more reserves from this point of view.

The close links between different sectors of the economy in each country, as well as similar links between countries, means that if any single branch of economic life is affected in this way, there will inevitably follow far-reaching consequences for the economy of a large region and even of the whole world.

6. A desirable strategy for mankind

Climatic changes will inevitably occur in the future. They will often be significant and may become irreversible in the decades immediately before us. They may be local, regional or global in their scope.

It is consequently essential that we develop a strategy: that we plan a set of long-term actions which will enable man to avoid the adverse consequences of possible climatic changes.

The first and basic element of such strategy is certainly a forecast of natural and man-made climatic changes. Though this requirement is a very difficult one, the outlook should not be regarded as hopeless. Valuable experience was gained in the GARP Atlantic Tropical Experiment and the First Global Experiment, and other related international scientific activities are already under way.

Thus we may be confident that scientific aspects of the requirement will be tackled although a considerable amount of time and continued international co-operation will be needed.

The second element of the strategy is an assessment of the consequences of the different types of climatic changes. Here the scientific problem is closely related to the socio-economic problem. The impacts of climatic change on economic development, and vice versa, are to be assessed in terms of future conditions. Consequently it is the future economic situation of individual countries that must be used in such an assessment. Estimates must be made for several decades ahead of the probable characteristics of agriculture, water supplies, industry, etc. Only in this way can adequate assessments be made of the effects of possible man-made climatic changes and of the possible impacts on man's activity of forecast climatic changes.

Such assessment is therefore feasible on the basis of taking into account long-term plans for national development in individual countries and, on the global scale, for the whole of mankind. In socialist countries, and also in some developing countries, such plans exist. Many other countries, however, have no overall plans of this kind and, in such cases a special type of forecast is required of future economic activity and of the state of different sectors of the economy. Such a forecast might be hardly more reliable than a climatic one.

Such assessments of favourable or unfavourable climatic changes, must be evaluated from a specific standpoint. What standpoint should we adopt in assessing the consequences of climatic change? that of the individual firm or large corporation? that of the individual citizen, the whole population of a country, or, of mankind as a whole? The objectives as well as the trends and prospects of economic development need to be considered from the standpoint that we adopt since the achievement of the objectives will be affected by favourable or unfavourable climatic changes. I am not likely to be contradicted if I suggest that the "prosperity of all mankind" is the goal of scientists. However, that is a vague phrase and the subject is a very complex and difficult one to resolve.

Several economists and sociologists have recently discussed these questions in a series of papers. One such is that written by a group of social scientists led by the well-known American economist Laszlo 8. This examines the objectives established by different countries of the world, by national governments, various public groups, international organizations, religious bodies and the like.

Laszlo is forced to draw what to us is the obvious conclusion that the real goals, which countries have in regard to economic activity by their governments and people, exist within socialist countries which plan and shape their development.

In capitalist countries the notion of a goal is absent; there are only desires for further development, and these vary among different organizations and public groups. Not surprisingly, there are no clear goals established, nor ways to achieve them, in the case of mankind as a whole. Laszlo calls for the development, adoption and pursuit of some rational objectives for all mankind, which he calls "a revolution of goals".

Here I would like to examine the very important question which was discussed in the paper by Dr. White 7, namely that some political and economic structures can be more vulnerable to climatic change than others. Let me give some examples from the history of the Soviet Union.

In 1831 a severe drought occurred in the Russian Empire resulting in the starvation which spread over vast areas with tens of millions of inhabitants.

In 1921 we faced a similar disaster in the same areas. Soviet Russia was ending the Civil War and the fight with interventionists. We were already in a weak state; and again drought led us to starvation and disaster.

In 1972 the drought was more severe than the other two and spread practically throughout the agricultural areas. However we already lived in conditions of developed socialism. Naturally the drought brought many troubles and slackened the pace of the fulfilment of the plan for economic and social development but there were no catastrophic consequences, no starvation. The food supply did not change at all throughout the country. Moreover in 1972 the grass crop was less than the 1971 crop and although less than had been planned it was still bigger than the average for the 5 previous years.

Furthermore although the general grain production and crop-yield are connected with climate conditions they are not affected by price changes, only other changes in the state of the market. It is always advantageous for the Soviet Union to increase food production, and in spite of the variations resulting from meteorological conditions, it is increasing. Steadily outstripping population growth, as is well known, the situation in other countries is not quite the same. Everybody can give his own examples.

The third element of the strategy is to make recommendations on how to avoid the adverse consequences of climatic change, or to avoid such change altogether.

Such recommendations are nowadays being developed and prepared in scientific papers. It is, for example, often suggested that fuel and energy use should be reduced in order to prevent the increase in the CO₂ content of the atmosphere or increased carbon dioxide absorption by the biosphere. Restriction of energy use is also recommended in order to preserve the planetary heat balance, etc. Some scientists have expressed rather strongly their fears that, without action of this kind, mankind will be faced by serious climatic changes during the next 50 to 100 years.

But to whom are these recommendations addressed, and who is to implement them? The answer is, presumably, politicians or so-called 'decision makers'.

The possibility of climatic changes is only one of the so-called "global problems" that affect mankind. Others include the provision of adequate food for the world's population, reduction of the still-increasing gap between developed and developing countries in economy, technology and other fields, the provision of energy, the rational use of water resources, the use of oceanic and space resources, and so on. Scientific publications increasingly reflect concern for such problems. It is essential that all scientists who are involved in such matters arrive at the conclusion that concerted action by many countries is necessary for these problems as a whole and every particular problem to be solved adequately and comprehensively on a global scale.

The actions that have been recommended vary. For example, in the "Limits to Growth" paper by Meadows' group 9 it was believed essential to put an end to continued expansion and growth. Mesarovic and Pestel 10, on the basis of more detailed calculations, conclude that further economic development is acceptable, but that its form needs to be agreed at the global level. The well-known American economist Leontiev and his co-workers 11 suggest that, within current natural limits, mankind can develop according to several different "scenarios", but he has nothing to say on what should be done in order to follow any one of them. A large group headed by another economist, Tinbergen 12, recommends the creation of a new world order, namely, a new system of co-operation among countries on a global scale including control of national economic and other activity by a supranational centre to which each state would transfer part of its sovereign rights.

Tinbergen, it may be noted, also mentions "decision-makers", whose agreement would enable the desired reconstruction of the world order. He considered that "the decision-makers" are national governments, international organizations (primarily the UN) and multinational corporations. However, neither Tinbergen nor the other authors appear to be interested in the real purposes of the agreement and the possibilities open to "decision makers".

We shall not here discuss the interesting and important questions of goals, incentives and the management of national economies; let us note merely that such matters depend on a country's social systems. Nevertheless concerted action by states all over the world to lessen, and then to solve, the urgent problems of modern civilization, the action for which the above mentioned authors are calling, is important now and will become absolutely essential in the coming decades. This can only be achieved through the co-operation of sovereign states on an equal basis for their mutual benefit. Such concerted action and co-operation already takes place in several fields where the interests of different nations coincide. International organizations like the World Meteorological Organization, the World Health Organization and many other similar bodies have functioned for more than a century. Similar co-operation is developing in the field of environmental protection, and agreements banning environmental damage for military or hostile purposes, preventing the pollution of the oceans, etc., have been concluded.

It is very important that, bearing all this in mind, we work towards a similar extension and strengthening of international co-operation. Of course, international co-operation in the solution of such global problems as possible climatic change is immeasurably more difficult to achieve than, say, co-operation in the World Weather Watch. However, it is more urgent. And the general relaxation of international tensions (détente) that has taken place during the last decade, despite the efforts of all those opposed to it, leaves us convinced of the feasibility of co-operation in different fields.

Dr. White suggests 7 that climatologists as well as other scientists should be prepared to go beyond their special problems into the fields of the social and economic phenomena. We have tried to indicate the line of action for scientists but we must also give governments and people the information they need to have.

To adapt the world economy to new climatic conditions, or to modify the climate on a global scale, so that adjustment of the economy is unnecessary, are each possible, given certain conditions. The vital conditions are:

- to prevent world conflict and establish a lasting peace, since only through the peaceful coexistence of countries with different social systems are close co-operation and concerted action on a global scale possible;
- to stop the arms race and promote disarmament, for only by such action will it be possible to afford the great material resources required by such concerted activities.

It is clear that only under such conditions can we hope to solve some other global problems of modern civilization.

Changes of climate in the coming century caused by natural and anthropogenic influence appear to be inevitable. I doubt whether, at this conference, we shall all agree on how the climate will change during the coming decades, but I hope that we can agree unanimously that mankind should develop an appropriate strategy so that it is prepared for such inevitable changes, and that peace, disarmament and international co-operation provide the foundations for such a strategy.

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GLOBAL ECOLOGY AND MAN

Bert Bolin*

1. General features of the biosphere

The characteristics of the biosphere are the result of development over millions of years. The size of the Earth, the distribution of land and sea (which has changed during geologic time), the chemical composition of the Earth's crust, water and a primordial atmosphere, and the characteristics of solar radiation provided the setting for life to begin. The development of living organisms, which began in the sea, gradually changed the composition of the soil, the oceans and the atmosphere. Oxygen became an important constituent of the atmosphere and enabled more advanced forms of life to develop. The first primitive ecosystems were successively replaced by more complex ones and the features of the biosphere gradually became very different from the original shell surrounding the proto-earth. This evolution did not only imply the "survival of the fittest" and the development of more versatile species, but also their mutual interplay to maintain approximately an overall stability of the global ecosystem and its subsystems while allowing a slow further development.

Natural changes of the ecosystems are generally slow in comparison with changes in society, with which we are familiar as human beings. We therefore usually cannot directly and easily observe these changes, which most likely still go on. We know, however, that, for example, the disappearance of the ice-sheets over north-west Europe and Canada 10 000 to 15 000 years ago was followed by a succession of ecosystems in these areas, leading to the characteristic set that we find today. The podzols and boreal forests which are characteristic of these areas are thus a result of ecological evolution during this time period. Most likely a climax has not yet been reached.

The activities of man on Earth have now reached such a pitch that he significantly influences both regional and global processes within the biosphere. In comparison with the natural rates of change these impacts are sudden and disturb the natural balances. Adjustments are initiated but, since these are slow, very considerable imbalances may exist for long periods. The consequences of man's impacts may therefore hardly be noticeable to begin with and the new quasi-balance towards which the system is striving is not usually understood at least for some time. We note, for example,

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that the Scandinavian podzols probably developed in a climate with much less acid precipitation than now prevails because of emissions of sulphur dioxide by fossil fuel combustion. As yet minor and usually only local impacts on the ecosystems have been directly observed, but we know very little about what these impacts may be over a century or longer. Similarly the exploitation of the tropical rain forests represents a very marked disturbance of the prevailing ecosystem. Since soil erosion may irreversibly change the conditions for their re-establishment it is difficult to foresee the long-term consequences of such major modification of an important subsystem of the biosphere.

It is obvious that the present features of the ecosystems on Earth are determined to a very considerable degree by the climate. The very marked differences between, for example, the tundra, the boreal forest, the savanna and the tropical rain forest are the result of the very different species and their interaction in characteristic biomes that have developed over millions of years. The opposite is also to some extent the case, but it is more difficult to establish the ways in which the biota influences the climate. Satellite pictures show differences in albedo (solar reflectivity) between different biomes. The water budget of a land area is significantly influenced by the characteristics of the vegetation cover. Accordingly the global hydrological cycle and thus important features of the general circulation of the atmosphere, are determined by the global distribution of biomes. It is, however, difficult to determine the magnitude of these feedback mechanisms. The living matter on Earth is part of the climatic system and we need to consider carefully the role of such matter when we are concerned with changes on time scales of centuries, millennia or longer.

Man's impact on the various ecosystems on earth is primarily local. The internal balance of any one of these depends on the energy input due to solar radiation and the flux of matter accomplished by the motions of air and water. These transport processes also interconnect the various subsystems. In this way man's impact on a local scale may also have regional and global implications. The study of the global coupling of the Earth's ecosystems is best accomplished by a careful analysis of the global biogeochemical cycles of the most important constituents present in organic matter, i.e., water, carbon, nitrogen, phosphorus, sulphur, and the key trace metals. The importance of such studies becomes even more obvious when we realize that man is already significantly and directly modifying these cycles, particularly because of the rapidly increasing use of fossil fuels as an energy source. Furthermore some of the chemical constituents released to the atmosphere by man have radiative properties that modify the fluxes of solar and terrestrial radiation through the atmosphere and thus possibly also influence the climate.

It should be clear from this very brief outline of the major aspects of the present topic that we are dealing with a very complex global system in which we particularly need to consider carefully long-term changes, both natural and man-induced. We shall begin with an overview of terrestrial and marine ecosystems, followed by a description of the main characteristics of the biogeochemical cycles. This will serve as a starting point for an analysis of the dynamics of the global ecosystem and its subsystems, including a discussion of their sensitivity to external influences, and the time scales of associated adjustment processes. In order to bring out more

clearly the importance of the dynamics of the global ecosystem for the study of climate and its variations, a few specific problems will be considered finally in some detail:

- (a) What is the most likely projection of the future increase of carbon dioxide in the atmosphere due to man's burning of fossil fuels and to changing land use?
- (b) Is man significantly changing the nitrogen cycle by increasing use of artificial fertilizers and by high temperature combustion?
- (c) What are the likely changes of the extent and characteristics of natural biomes which would occur if the global climate were to change significantly?
- (d) Does man influence the global climate by modifying some basic features of the biosphere?

2. The terrestrial biosphere

2.1 Basic biome types and their dependence on environmental factors

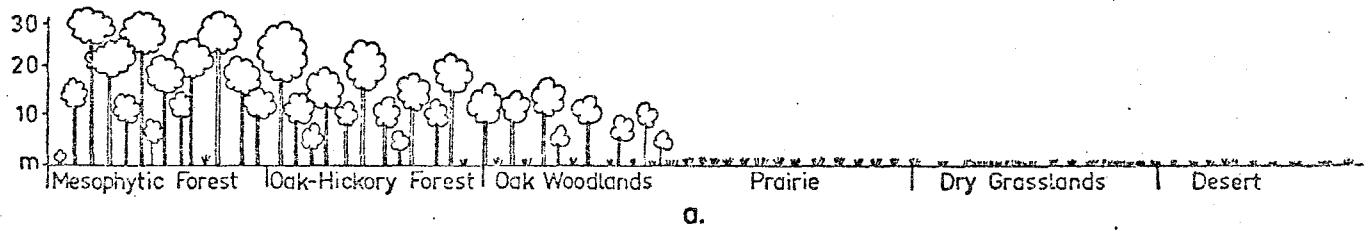
We may distinguish between six major types of land 1:

- (a) Forest;
- (b) Grassland;
- (c) Woodland (small trees with well developed undergrowth);
- (d) Shrubland (coverage of shrubs and other plants generally above 50 per cent);
- (e) Semi-desert;
- (f) Desert (plant cover generally less than 10 per cent).

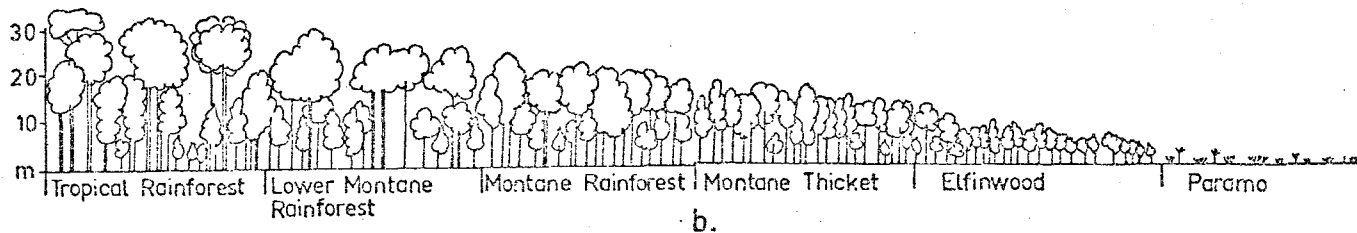
These are found in such different environments that several biome types are defined within each.

The transitions from one biome type to another may be abrupt but are generally gradual, depending primarily on climate but also on other environmental factors. Figure 1 describes two such ecoclines as dependent on:

- (a) Increasing aridity from rain forest to desert in South America; and
- (b) Temperature gradient from tropical seasonal forest northward to Arctic tundra.



a.



b.

Figure 1. Ecoclines along a gradient of

- (a) increasing aridity from rain forest to desert in South America
- (b) decreasing temperature from tropical seasonal forest to Arctic tundra I

The relation between biome types and climate can be described schematically in a diagram as reproduced in Figure 2. The boundaries between the various types are, of course, approximate and depend, for example, on soil types, even though the soil also is a product of the biome itself (see 2.2 below).

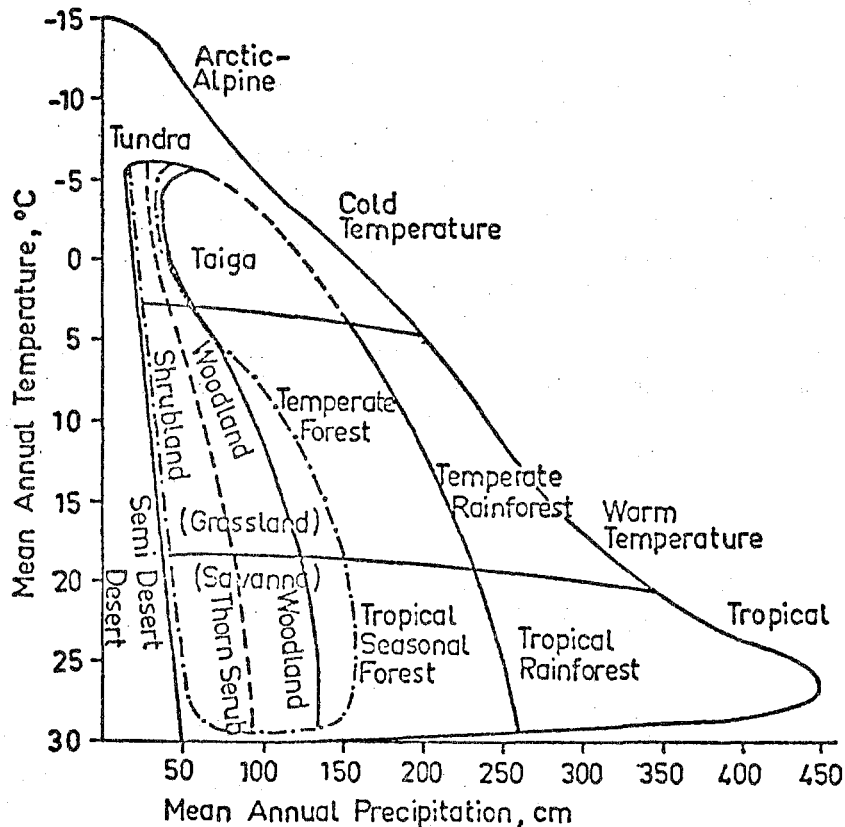


Figure 2. World biome types in relation to mean annual precipitation and temperature. Boundaries between types are approximate. The dot-and-dash line encloses a wide range of environments in which either grassland or one of the types dominated by woody plants may form the prevailing "vegetation" 1.

Most biomes are in a slow transitional state. Due to biological activity lakes in a terrestrial biome gradually diminish in size and ultimately disappear. After destruction of a forest by fire, or clear cutting or after the abandonment of farm fields, a succession leads back to forest. The time required for these processes to restore the biome is generally longer in cold than in warm climates, and depends on the specific biome. The community that ends such a succession is called a climax. It is stable in the sense that birth rates and death rates are in balance. Gross primary production of living tissues is equal to total respiration and breakdown of organic matter. Energy balance also prevails, i.e., solar energy used in photosynthesis is equal to the energy release by respiration and decay. An approximate nutrient balance

exists, and the small amounts being lost by river run-off, and through ground water, are balanced by deposition from the atmosphere. Ecosystems close to a climax state change slowly, however, over longer periods of time, for example because of slow climatic changes.

2.2 Characteristic soil types

The existing soil types on Earth have been formed in interaction between living communities and a geological substrate. They are mixtures of inorganic and organic substances. Weathering of the substrate is due to a combination of physical effects (e.g., temperature changes), chemical effects (e.g., due to exposure to water, oxygen, acids) and biological effects (e.g., cracking of rocks by roots). The soil is not an inert substance, but part of the ecosystem. The plant community develops and influences the soil which contains dead organic matter, living roots, fungi and bacteria. The soil is in itself a living community.

Soils may be classified as a function of temperature and precipitation, as indicated schematically in Figure 3, in a manner similar to what was shown for the biomes. This implies that there is a general, but by no means unique, relation between biomes and soil type.

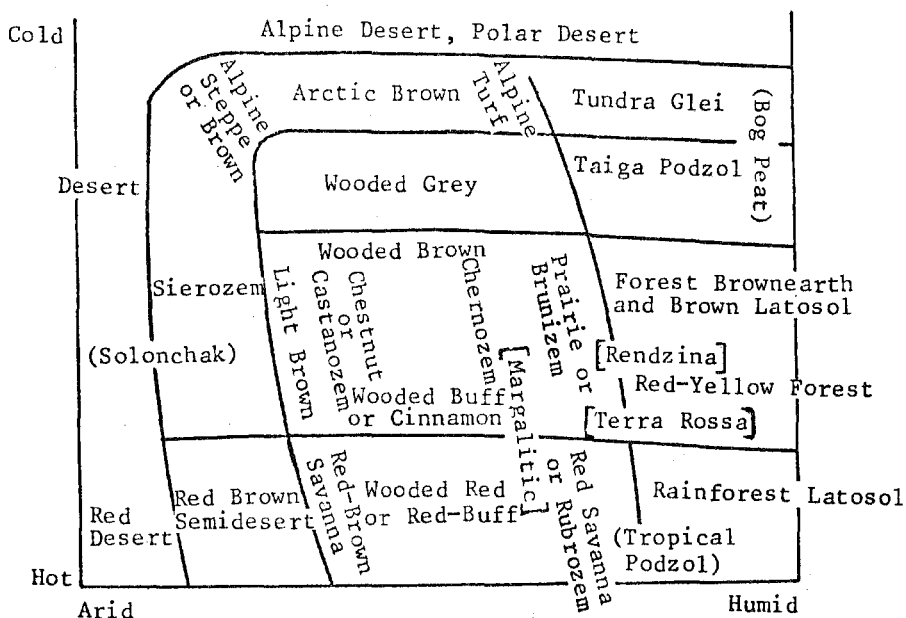


Figure 3. Great soil groups in relation to climate. Both non-grass and grass dominated communities occur and form different soils. Those formed in grassland communities are written vertically, those formed in woodland, shrubland or tundra are written on the horizontal. Soils formed on limestone are indicated in brackets and those formed with special conditions of water movement in parenthesis 1.

As mentioned, the soils are usually in a dynamic quasi-equilibrium, in which the physical, chemical and biological processes interact. Some rapid cycles, such as that of water, are maintained, whereas others are slower like some of the nutrient cycles. The latter may, however, differ, depending on soil type and climate. Generally the characteristic time scales are shorter in tropical latitudes than in polar regions. Thus the nutrient content of some tropical soils (such as those of the rain forests) is quite low, and they are accordingly more sensitive to external disturbances. The other extreme is represented by peat bogs, in which organic matter decomposes very slowly. Hence they also adjust to external influences only gradually.

3. The marine biosphere

Life in the oceans primarily develops in the photic zone, i.e., the top few tens of metres, where solar radiation is adequate for photosynthesis. The amount of carbon in the form of carbonate and bicarbonate ions is generally sufficient for phytoplankton to grow if the supply of nutrients, i.e., fixed nitrogen phosphorus and trace metals, is sufficient. Usually nitrogen and phosphorus limit the rate of primary production by photosynthesis, even though algae are able to "fix" nitrogen, using the dissolved nitrogen gas in sea water. Zooplankton feed on the phytoplankton and in turn serve as food for higher animals in the predator-prey chain. When plankton and animals die, bacterial decomposition and chemical dissolution begin, whereby nutrients are again supplied to the water and become available for renewed primary production. Some organic compounds that become dissolved in the water, however, decompose only slowly. At any one time the total amount of dissolved organic matter in the sea as a whole is about 200 times greater than the amount of living plants and animals. Dead plankton, particularly zooplankton, and fecal pellets that are comparatively large in size, sink to deeper strata of the oceans while being decomposed. An effective mechanism for downward transport of carbon and nutrients in the oceans is thereby initiated. The bacterial decomposition of these materials requires oxygen. At the sea surface the oxygen consumed is rapidly replaced by oxygen released during photosynthesis, a process which often goes on simultaneously. If necessary, oxygen is also transferred from the ocean surface. Oxygen transfer to deeper layers (below a few hundred metres) is slow, and for this reason an oxygen minimum is generally found at depths between 500 and 1 500 m. Exchange of water between the cold surface waters at higher latitudes and these intermediate layers of the oceans maintains a flux of oxygen to balance the consumption due to bacterial decomposition. This exchange conversely also brings water enriched in phosphorus and nitrogen (and also carbon) to the sea surface in high latitudes and in areas of upwelling in association with the major ocean currents.

Obviously the processes of photosynthesis in the surface layers initiate internal oceanic cycles of the constituents involved. Of particular interest in the present context are the cycles of carbon, oxygen, nitrogen and phosphorus. These compounds are involved in photosynthesis in the approximate proportions $C : O : N : P = 100 : -130 : 15 : 1$, where the minus sign indicates that oxygen is released during photosynthesis, whereas the others are incorporated into the organic material being formed. It is clear that these cycles are interlinked in the proportions indicated above.

The characteristic times for the various processes vary greatly. The life time of individual organisms in the surface layers of the ocean is merely hours or days. The innermost cycle of those described, i.e., phytoplankton → zooplankton → bacterial decomposition → return of nutrients to the water in the surface layers, takes place in a matter of weeks. The turbulent motions in the surface layers are effectively maintained by winds, heating, cooling and evaporation processes. The uppermost 100 m or so are thereby reasonably well mixed in the course of weeks or a month. The thermohaline circulation involving the intermediate waters has a characteristic time scale of a few decades to half a century, while the deep sea water is renewed in the course of 500 to 1 500 years.

The description given above is of course exceedingly simplified. An adjacent sea, such as the Mediterranean for example, may supply water rich in oxygen to intermediate levels in the Atlantic, since it has relatively high salinity, and its outflow therefore sinks when leaving the Gibraltar Strait. Upwelling in association with the major ocean currents, particularly in coastal and equatorial regions is also of importance for the vertical turnover of the oceans. It contributes to the supply of nutrients to the photic zone and thus to the primary production. The simple overall circulation described above will, however, suffice for our present purposes.

4. Global biogeochemical cycles

It is clear from the presentation so far that the motions of air and water and their interplay with chemical and biological processes within the terrestrial and marine biosphere initiate the global biogeochemical cycles of carbon, oxygen, nitrogen, phosphorus, sulphur and a number of other elements. Depending on the differing chemical characteristics of these elements, and their role in organic compounds, their circulations in nature are quite different. Some elements, for example, are abundant in the atmosphere and accordingly have long residence times, and are well mixed. Others are rapidly returned from the atmosphere to the soil or the sea, and show marked spatial variations. Some reasonably detailed pictures of their features are essential for an understanding of the dynamics of the biosphere as a whole. This is necessary when one considers the role of the biota and global ecology for the climate and vice versa, since the characteristic mixing time for the troposphere is about one year. We shall next present such general descriptions of the cycles of carbon, oxygen, nitrogen and sulphur.

4.1 The carbon cycle

An attempt to summarize our present knowledge about the magnitude of the reservoirs (pools) of carbon in nature and the fluxes between (and within) them is given in Figure 4 based on the review by Bolin et al [2]. Units are in 10^{15} g y^{-1} (Pg y^{-1}).

At present (1978) the atmosphere contains about 695 Pg (c. 330 ppm, parts per million by volume), which is an increase from about 660 Pg (c. 313 ppm) during the last 20 years for which accurate observations are available. Figure 5 shows a summary of the measurements during this time period [3, 4]. Twelve month running means or annual averages have been plotted. The long-term trend is firmly established as are also some interannual variations that are probably associated with climatic oscillations in the southern hemisphere.

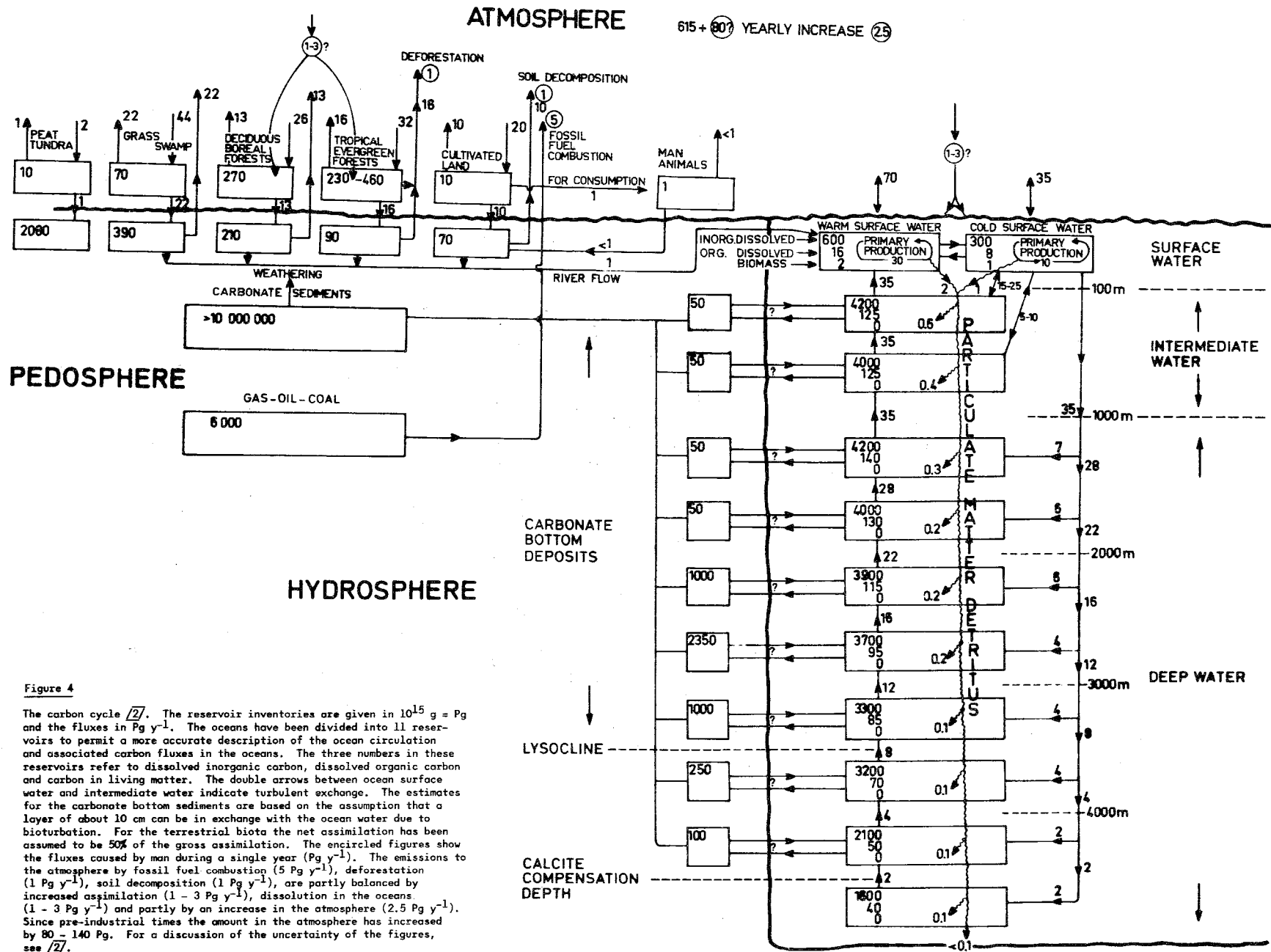


Figure 4

The carbon cycle [27]. The reservoir inventories are given in 10^{15} g = Pg and the fluxes in Pg y^{-1} . The oceans have been divided into 11 reservoirs to permit a more accurate description of the ocean circulation and associated carbon fluxes in the oceans. The three numbers in these reservoirs refer to dissolved inorganic carbon, dissolved organic carbon and carbon in living matter. The double arrows between ocean surface water and intermediate water indicate turbulent exchange. The estimates for the carbonate bottom sediments are based on the assumption that a layer of about 10 cm can be in exchange with the ocean water due to bioturbation. For the terrestrial biota the net assimilation has been assumed to be 50% of the gross assimilation. The encircled figures show the fluxes caused by man during a single year (Pg y^{-1}). The emissions to the atmosphere by fossil fuel combustion (5 Pg y^{-1}), deforestation (1 Pg y^{-1}), soil decomposition (1 Pg y^{-1}), are partly balanced by increased assimilation ($1 - 3 \text{ Pg y}^{-1}$), dissolution in the oceans ($1 - 3 \text{ Pg y}^{-1}$) and partly by an increase in the atmosphere (2.5 Pg y^{-1}). Since pre-industrial times the amount in the atmosphere has increased by 80 - 140 Pg. For a discussion of the uncertainty of the figures, see [27].

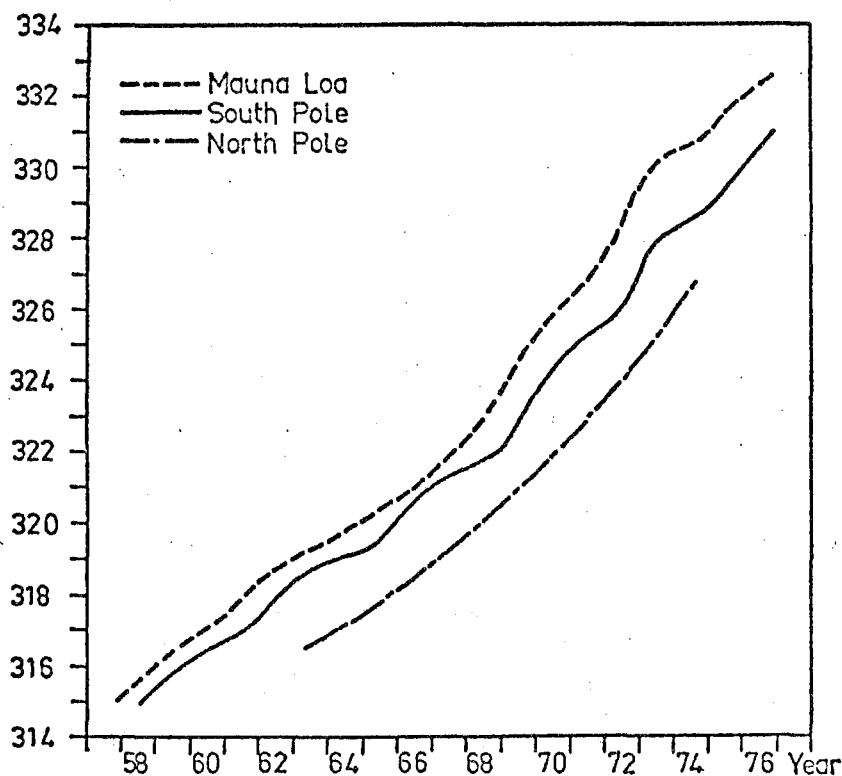


Figure 5. Seasonally adjusted concentrations of atmospheric CO₂ at Mauna Loa (Hawaii), South Pole 3 and as measured from commercial aircraft in North Pole regions 4. The North Polar curve is a second degree polynomial deduced from average annual values which have not been corrected by intercalibration with the two other data series.

The total amount of inorganic carbon in the sea is about 36 000 Pg, of which most is in the form of bicarbonate ions. It is approximately evenly distributed with only 5 - 10 per cent more per unit volume in the deep sea water. There is furthermore about 1 000 Pg of carbon in the sea in the form of dissolved organic matter. In contrast to these numbers there is only about 4 Pg at any one time locked in living organic matter primarily phytoplankton.

The exchange of carbon in the form of carbon dioxide between the atmosphere and the sea is quite rapid, the average residence time for a CO₂ molecule in the atmosphere being 5 - 10 years. This means a gross transfer across the sea surface of about 100 Pg y⁻¹. The primary production in the sea is estimated at about 40 Pg y⁻¹, which implies an average residence time for carbon in living matter in the sea of about 1 month. The corresponding time for carbon in dissolved organic matter is probably considerably more than 1 000 years but this does not exclude the possibility that a rapid transfer plankton → dissolved organic matter → dissolved inorganic matter takes place in the top layers of the ocean. The overall circulation of carbon in the

oceans including the deep sea is essentially determined by the slow thermohaline water circulation with a characteristic time scale of 500 to 1 500 years. For further details reference is made to Figure 4 where the interior transfers in the oceans are also indicated approximately.

About 800 Pg carbon is stored on land as living organic matter. Of this amount approximately 90 per cent is found in the forests. The net primary production is 50 - 75 Pg y^{-1} , but this is only about 50 per cent of the gross primary production, the other half being returned quickly to the atmosphere by respiration. Less than half, about 20 Pg, is assimilated in the forests and roughly half of this amount is transformed into wood. The remainder appears as leaves, needles, or grass, which have a rather short life time. The figures given above yield an average transit time for carbon in wood of about 70 years, while the corresponding value for carbon in the living organic pool as a whole is only 12 - 15 years.

The estimates of the total amount of carbon in the soil vary between 1 000 and 3 000 Pg. The uncertainty largely depends on the different values for the pool of carbon in the form of peat. Since the amount of peat formed annually is small and the transit time for carbon through this pool is thus large (several thousand years) this uncertainty in the estimate is of minor significance when one is concerned with changes that occur during less than a few centuries. The average transit time for carbon through soils other than peat is only a few decades, a value which varies considerably with latitude, i.e., climate. Bacterial decomposition is slow in cold climates in, for example, podzols, but fairly rapid in the soils of tropical rain forests. Even though direct information is limited, the average transit time probably differs by a factor of ten between these soil types.

Man has already modified the carbon cycle to some extent by exploiting for agriculture land areas that were previously covered by forests. A net transfer of carbon to the atmosphere has thereby occurred. Extensive agriculture increases the rate of decomposition of dead organic matter in the soil, whereby a net flux to the atmosphere has also taken place. It is difficult to assess the accumulated flux of carbon dioxide to the atmosphere due to changing land use during the last few hundred years, during which the world population has increased by more than a factor of five. There have been attempts to estimate this total emission on the basis of the observed decrease of the isotope carbon-13 in the tree-rings [5]. As yet too few samples are available and therefore the conclusions are still uncertain. The data indicate, however, that of the order of 100 Pg may have been transferred to the atmosphere due to the clearing of forests and the expansion of agriculture. The annual input at present is estimated at between 1 and 5 Pg [6, 7], primarily due to deforestation in tropical latitudes.

In addition man has been burning fossil fuels at an accelerating rate since the middle of the last century. Altogether about 140 Pg of fossil carbon has been emitted into the atmosphere in this way during the last 125 years. The annual input has increased at a rate of about 4 per cent per year since the last world war, but has remained almost constant since 1974 at a level of about 4.5 Pg y^{-1} . Observations of the CO₂ concentration in the atmosphere show an annual increase during these later years of about 2.2 Pg, i.e., about half of the output due to fossil fuel combustion. Considering also the CO₂-transfer to the atmosphere due to changing land use, we

arrive at the conclusion that the airborne fraction may have been anywhere between 30 and 50 per cent during the last 20 years, the most likely value being 40 - 45 per cent. On the basis of these figures we estimate the concentration of CO₂ in the atmosphere before 1800 to have been between 265 and 290 ppm. Direct measurements from the last century are uncertain because of possibly unrepresentative sampling sites and of less accurate analytical techniques than are available today. The data indicate, however, that it is more likely that the preindustrial value was in the upper part of the range indicated.

The total emissions to the atmosphere due to man thus seem to have been between 180 and 240 Pg, while the increase in the atmosphere has been between 75 and 130 Pg. To which other reservoirs has the remainder been transferred? As the CO₂ concentration in the atmosphere has increased, a net transfer to the oceans has undoubtedly occurred. The surface layers adjust fairly quickly to such higher CO₂ partial pressures, but due to the particular chemical characteristics of the carbonate-borate system of sea-water the increase of the carrying capacity of the surface layers is only about 10 per cent of that of the atmosphere. As has been indicated above, the surface layers of the ocean exchange quite slowly with the deep sea. It is not likely that an appreciable amount has been transferred to the deep sea. Observations of the increase of the radiocarbon (¹⁴C) and tritium at intermediate depths (down to 1 000 to 1 500 m) indicate on the other hand that these layers may have served as an important sink /8/. It is difficult to assess quantitatively the magnitude of this transfer and it is doubtful if all of the excess carbon can be found in these layers of the world oceans.

Plants assimilate more effectively if the partial pressure of the CO₂ in the air increases and if there are no other limiting factors for growth. Greenhouse experiments show this effect clearly. It is difficult to assess what these measurements imply for the biosphere as a whole because of the varying environmental conditions that prevail for different biomes. It is likely, however, that some increased assimilation and accumulation have taken place in the biota untouched by man. Whether this in the long run will lead to an appreciably larger pool of carbon in the terrestrial biosphere or not is another question. It may primarily mean a more rapid turnover, but not an appreciable increase in the pool itself. At present we do not know the answer to this question. We shall return to a more detailed discussion, when we are assessing the likely future changes of the atmospheric carbon dioxide concentrations due to man's interventions.

4.2 The oxygen cycle

The existence of oxygen in the atmosphere is fundamental to the existence of life on Earth and vice versa. The development of life on Earth was closely associated with the development of oxygen in the atmosphere. Ultraviolet radiation from the sun, which is destructive to the living cell, dissociates oxygen molecules and initiates thereby a series of photochemical reactions that are necessary for the formation and maintenance of an ozone layer. The ozone molecule in turn absorbs very effectively the ultraviolet radiation in the critical spectral interval 0.2 - 0.3 μ m, to which living matter is very sensitive. At an early stage of the development of an atmosphere around the Earth its oxygen content probably was low, and the ozone layer was located close to the Earth's surface. Gradually oxygen accumulated in the atmosphere and the

ozone layer was pushed to higher levels; it now has its maximum at an elevation of 25 - 30 km. In the course of this development the composition of the lower atmosphere has probably changed with regard to the occurrence of a whole series of minor constituents. Some of these, notably water and nitrogen oxides, also play an important role for the photochemical balance that prevails in the ozone layer. It is likely that this balance is quite different from that which was established in an early phase of the development of the Earth's atmosphere. In this sense the biogeochemical processes at the atmosphere-earth-sea interface have played a role in the establishment of the present distribution of ozone in the atmosphere. The temperature maximum in the upper stratosphere, which is maintained by the existence of a layer of ozone, and the present distribution of radiative fluxes through the atmosphere, are in this way indirectly influenced by the biogeochemical processes in the troposphere and at the Earth's surface. Even though this development has occurred over a time period of millions of years, it is a striking example of the complex interplay that has created and now maintains the present environment. It also shows how the prevailing climate is dependent in some respects on atmospheric chemical processes.

4.3 The nitrogen cycle

Nitrogen is a key element for building the cells of which all living matter is composed. It occurs in the protein molecules which determine cell structure and function, and in those sites of the nucleic acid molecules which are responsible for the faithful duplication and transmission of inherited information, i.e., the DNA-molecule. Molecular nitrogen is the predominant constituent of the atmosphere, but most organisms cannot use it as such. The conversion or "fixation" of molecular nitrogen into generally biologically available compounds is a process fundamental to the maintenance of life.

The nitrogen cycle is complex because of the many oxidation states in which nitrogen can occur, from -3 (NH_3) to +5 (NO_3^-). Figure 6 is an attempt to summarize the main features of the nitrogen cycle in accordance with three recent surveys /9, 10, 11/. We shall not, however, discuss in any detail the complex photochemistry of the atmospheric compounds.

The uptake of nitrogen into the biomass on land and in the sea is the core of the cycle. We note that these two fluxes are of about the same magnitude, $2\ 000 \cdot 10^{12} \text{ g y}^{-1}$ ($= \text{Tg y}^{-1} = \text{M ton y}^{-1}$). In comparison the pools of fixed nitrogen from which these fluxes take place are large. In the soil organic matter contains an estimated amount of 300 000 Tg, which yields a mean transit time for nitrogen through this major reservoir of about 100 years. Tropical soils contain comparatively little organic matter and the transit time there is considerably less. The opposite is true for the transit time through soil organic matter in temperate and polar climates. Since fixed inorganic nitrogen is soluble (NO_2^- , NO_3^-) comparatively small amounts accumulate in the soil in this form. In the oceans on the other hand soluble inorganic nitrogen compounds represent a major pool, which is probably larger than that of dissolved (dead) organic matter. The mean transit time between these two pools on the one hand and the biomass on the other is of the order of 500 years. It is closely related to the water exchange between the intermediate and surface layers of the oceans. Because of its role as an essential nutrient for plankton, nitrogen is quickly

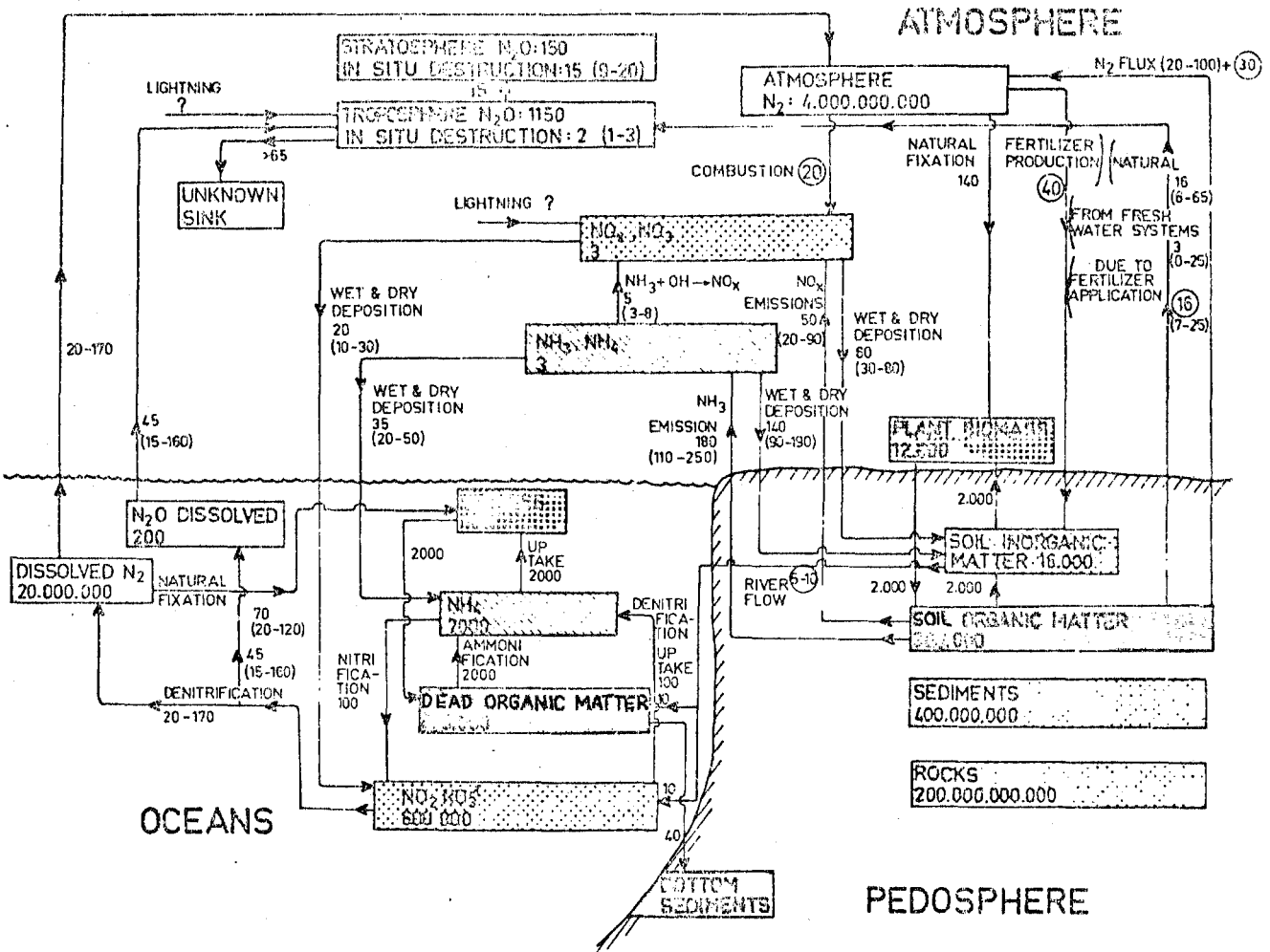

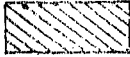

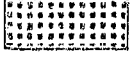



Figure 6 - The nitrogen cycle [5, 6, 7]. The estimates of the inventories are given in 10^{12} g = Tg and the fluxes in $Tg\ y^{-1}$. In many instances attempts have been made to give the range of uncertainty of the estimates, which is then indicated within parenthesis. Man's modification of the nitrogen cycle has been shown by encircled figures. The nitrogen cycle is characterized by a number of chemical transformations and some indication of this fact is given by shadings of the reservoirs.

Key to shading:

-  Inorganic nitrogen compounds in oxidized form, except N_2O (valence ≥ 2)
-  Inorganic nitrogen compounds in reduced form (valence ≤ -1)
-  N_2O (valence 1)
-  Nitrogen in living matter
-  Nitrogen in dead organic matter

consumed in the photic zone and needs to be replaced from deeper layers where it is released by bacterial decomposition of particulate and dissolved organic matter. The nitrogen cycle in the sea is, however, much more complicated than this simple scheme indicates and is not well understood in detail.

The magnitudes of reservoirs and of fluxes in the atmosphere are generally much smaller and the same is true for the mean transit times through the atmosphere, particularly for $\text{NO}_2/\text{NO}_3^-$ and $\text{NH}_3/\text{NH}_4^+$, which are of the order of a few days. There are therefore very marked spatial variations of these compounds in the atmosphere and the average picture shown in Figure 6 is not representative for any one limited region. The natural emissions to the atmosphere are due to the formation of volatile compounds, namely, NH_3 , $\text{NO}-\text{NO}_2$, N_2O (and N_2) during the process of bacterial decomposition in the soil. In the atmosphere the first two compounds are incorporated into cloud and rain drops as NH_4^+ and NO_3^- ions and are returned to the soil and the sea by precipitation and particle deposition. N_2O on the other hand is not significantly dissolved in this way but instead decomposes into NO in the stratosphere and, as already mentioned in the previous section, plays an important role there in the chain of photochemical reactions associated with ozone. However, it has not yet been possible to identify all atmospheric sinks for N_2O in the troposphere, a problem which represents a very significant uncertainty of our view of the nitrogen cycle.

Some of the bacterial decomposition, both in the soil and in sea water, leads to the formation of N_2 , which is a loss of fixed nitrogen. This is compensated for by natural fixation amounting to about 140 Tg y^{-1} by bacteria and algae in the soil and about 70 Tg y^{-1} , primarily by blue-green algae, in the sea. A balance between losses and gains has been established by the global ecosystem in the course of the evolution of the biosphere.

Man is today significantly modifying the nitrogen cycle. First of all the introduction of monocultures with legumes that can fix N_2 through symbiosis with certain bacteria probably implies a net increased fixation. On the other hand modern agriculture has increased the rate of decomposition of organic matter in the soil and thus the return of N_2 to the atmosphere. About 40 Tg y^{-1} fixed nitrogen is produced in the form of fertilizers, and high temperature combustion adds another 20 Tg y^{-1} to the atmospheric pools. This is about 30 per cent of the natural fixation, and the rate is increasing rapidly. However, the amount of nitrogen fixed by man annually is still small compared with the existing pools in the soil and in the oceans. These pools will therefore be influenced only slowly. It will take several decades, maybe a century or even more, before significant global changes may be expected due to man's activities, except locally in some soil and water systems. We need, however, particularly to watch out for changes in the N_2O balance in the atmosphere, since its dissociation in the stratosphere produces NO , which in turn plays a role in the decomposition of the ozone [12]. It may be true that it will be long before significantly larger N_2O emissions occur from the Earth's surface, but this also implies that it will take a long time for conditions to return to an earlier balance once a change has occurred. Continued monitoring of the N_2O concentration in the atmosphere is an urgent task.

4.4 The sulphur cycle

Sulphur is another element in the living cell that we need to consider in some detail, since man's manipulation of the sulphur cycle is noticeable on a global scale, and since sulphate in particulate form is an important air pollutant. The main features of the global sulphur cycle are shown in Figure 7, where the light numbers show the fluxes in $Tg\ y^{-1}$ before man intervened and the heavy ones are the fluxes caused by man. 13.

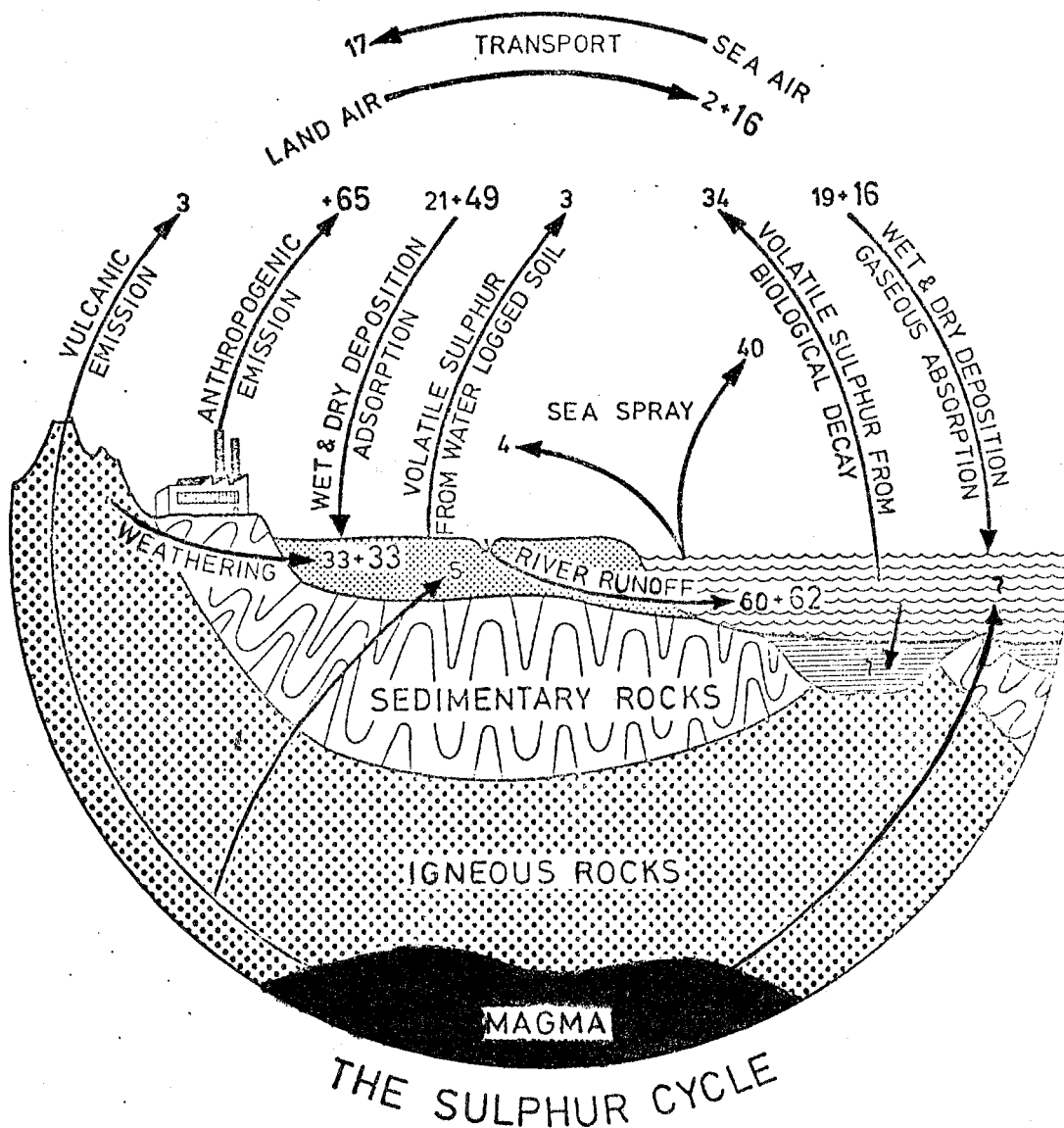


Figure 7. The sulphur cycle 13. The fluxes are given in $10^{12}\ g\ y^{-1} = Tg\ y^{-1}$. The light figures represent conditions before man significantly influenced the sulphur cycle and the heavy figures show the changes in the fluxes due to man.

The major processes maintaining the cycle are the inclusion of sulphur in living matter, the bacterial decomposition of dead organic matter, whereby volatile sulphur compounds (H_2S , dimethylsulphide) are released to the atmosphere, and weathering in the soil. Since sea water contains appreciable amounts of sulphur, an additional process is brought about by wind-borne sea-salt aerosols. Estimates of the flux of volatile sulphur compounds to the atmosphere are still quite uncertain, and have been reduced by a factor of about five since the first ones were made about 20 years ago. In the meantime man's emissions of sulphur to the atmosphere, primarily due to combustion of fossil fuels, have increased quite considerably. The anthropogenic emissions of sulphur are at present of the same size as those due to natural processes on a global scale and may in industrial regions be more than ten times the natural ones. Obviously man is modifying the sulphur cycle very significantly.

Emissions to the atmosphere due to man are almost entirely as sulphur dioxide, in which form it hardly plays a climatological role. The sulphur dioxide may be oxidized to form small particles or it may be oxidized in the cloud and water droplets and removed by precipitation. A considerable part is, however, deposited directly on water surfaces or vegetation. The turn-over time for sulphate particles is about three days. It has been well demonstrated that the sub-micron aerosol that is almost constantly found around the major industrial areas of the world consists to a considerable extent of sulphate. It has also been shown that this pollution significantly influences the short wave radiative climate of these regions. It is unclear if and how the long wave radiation is changed.

The formation of sulphate aerosols also implies acidification of the clouds and rain in industrial areas. The acid which is thereby added to the soil is still rather small in most areas, but the soils least buffered, such as podzols in formerly glaciated areas, may possibly have been somewhat modified. This cannot yet be directly verified by measurements. It should be emphasized that continued emissions and deposition of sulphuric acid may gradually change the present chemical soil characteristics. We note that so far the fossil fuels containing least sulphur have been used preferentially and that, as yet, merely a few per cent of the fuel reserves have been exploited. Significant impacts on the biosphere may ultimately occur in regions with the most sensitive soils if a substantial part of the fossil fuel reserves are used without appreciable removal of the sulphur.

5. Dynamics of ecosystems and climate

The way climate, primarily temperature and precipitation, determines the characteristics of biota and soil was briefly outlined in Section 2. The response of an ecosystem to changing environmental conditions requires a more detailed analysis. It is important to distinguish between the instantaneous, intermediate and long-term responses, which we shall discuss separately.

- (a) Instantaneous ecosystem response. Most field studies and ecosystem modelling have aimed at the determination of the rate of assimilation and respiration, i.e., net primary production, as functions of the basic characteristics of the biome (leaf area, canopy structure, etc.), and as dependent on environmental parameters (temperature, humidity, soil

moisture, solar radiation, nutrient content of the soil, carbon dioxide concentration in the atmosphere). A careful analysis of the vertical distribution of all relevant parameters through the canopy is required to determine the total assimilation by vertical integration of the photosynthesis as a function of height (see for instance 14, 15). The aim of this work has usually been to determine the optimum conditions for production in agriculture and forestry. However, it also yields important information on limiting factors for growth under various circumstances and on the response of the ecosystem to changing environmental conditions.

If the water supply is adequate most biomes develop an amount of assimilating foliage (leaves, needles, green stems, etc.) that permit them to utilize more than 95 per cent of incident radiation. The rate of assimilation is temperature dependent, even though an appreciable reduction only occurs for fairly large departures from the optimum temperature, which in turn is different for the various biomes (compare Figure 2). The reduction of assimilation in the early afternoon is primarily due to insufficient water supply, particularly in dry climates. The stomata close in order to reduce evapotranspiration. At such times higher CO₂-concentrations in the air would permit higher assimilation rates, since the transfer in through the stomata is primarily controlled by diffusion, and thus by the concentration difference between the surrounding air and the stomata. It should be clear from this much-simplified description of some key relations during the photoassimilation that the response of a given biome to varying environmental conditions can only be obtained by rather complex model computations. The tools for such computations are, however, available (compare the overview paper by Baumgartner to this conference).

- (b) Intermediate range ecosystem response. If abnormal climate prevails for some years or decades, the biome adjusts to the new environmental conditions by developing a modified climax structure. The density of a forest or the canopy characteristics may change in order to optimize the primary production under the new environmental conditions. The change towards a new optimum implies an inherent stability of the biome.
- (c) Long-term ecosystem response. If a marked climatic change takes place and lasts for a long time (a century or more, i.e., considerably longer than the normal life time of members of individual species in the biome) a succession to another biome may be initiated. This would most likely happen in the vicinity of a transition between two existing biomes. In the course of a century or more the soil would also change considerably. Our only knowledge of such transitions is meagre and is based on the changes that have occurred in the past when climate has changed.

We shall make use of some of the above considerations in the following section.

6. Some problems of major concern

6.1 Assessment of likely future increase of atmospheric carbon dioxide due to man's activities

The total fossil fuel reserves have been estimated to be at least 5 000 Pg, of which about 90 per cent is in the form of coal. This reservoir is considerably greater than that of living and dead organic matter on land. We have previously indicated that the deep sea cannot have been a very significant sink for the excess carbon dioxide emitted to the atmosphere, while the intermediate waters may have played an important role. We do not know, however, to what extent the terrestrial biosphere may also have served as a sink, primarily those forests of the world that have not yet been exploited by man, or those that are subject to careful management in order to increase the stock of standing timber. Any projection of possible future increases of the atmospheric CO₂ concentration will depend greatly on our assumption regarding the partitioning of the excess carbon dioxide between these two major pools. If we assume that the terrestrial biosphere will not be a significant sink we deduce that 70 to 80 per cent of the total emissions due to burning of fossil fuels (5 000 Pg) would remain in the atmosphere because of the buffering effect of sea water. The atmospheric concentration would rise to above 2 000 ppm, see Figure 8 /3/. This means a sevenfold increase as compared with the preindustrial condition. Very significant changes of the radiation balance of the earth would undoubtedly occur. In no case, however, would toxicity to man and animals become a hazard.

Another extreme projection /16/, envisages a very drastic increase in the amount of carbon in the terrestrial biosphere; it suggests that the increase in the atmosphere would only be temporary (lasting a century or somewhat more) with a maximum concentration of only 700 - 800 ppm as indicated in Figure 8. This latter projection seems, however, quite unlikely. It is based on the assumption of a rapid increase of photosynthesizing matter, which is contrary to the dynamics of most existing ecosystems as indicated in Section 5. It should also be recalled that the rapidly increasing world population will probably require the use of all land suitable for agriculture within half a century. This will mean a further substantial reduction of the extent of forests. Furthermore few forests will be untouched by man 50 - 100 years from now, which will probably mean less possibility for the terrestrial biosphere to serve as a potential sink since climax conditions would not be reached before cutting. Also modern ways of preparing the soil for plantation increase the decomposition of organic matter in the soil. As a matter of fact, it even seems likely that the carbon pool in the terrestrial biosphere may decrease as a result of continued forest exploitation.

Man's use of fossil fuels and rate of interference with the terrestrial biosphere will probably not change very rapidly, but will continue to grow as world populations grow. For a few decades, or even longer, the relative contributions of these processes to the increase of atmospheric CO₂ will probably remain essentially unchanged. It is therefore likely that until the end of this century, or until the first decade of next century, the increase in the atmosphere will be fairly close to 50 per cent of the fossil fuel releases. A continued annual increase of the fossil fuel combustion by 4 per cent would yield an atmospheric CO₂ concentration of about 380 ppm at the turn of the century. For a 2 per cent increase the corresponding figure would be about 365 ppm.

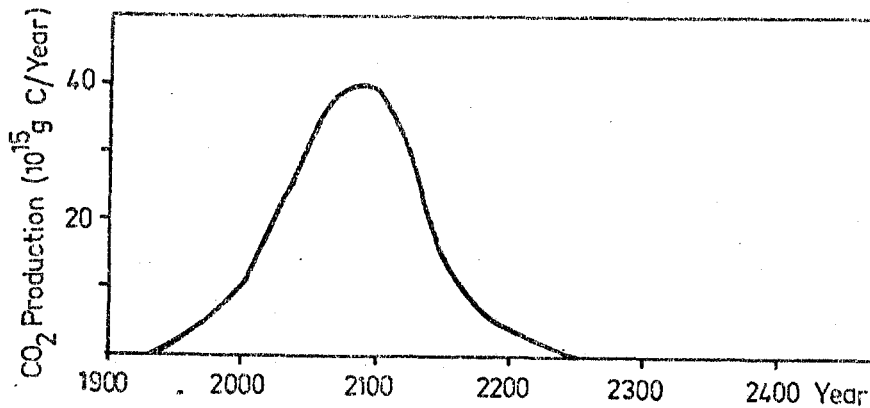


Figure 8a. Industrial CO₂ production for an assumed total output of 5 000 Pg, a consumption of 4.6 Pg y⁻¹ in 1975, increasing annually at a rate of 3 per cent until half the reserves have been consumed. Thereafter consumption declines gradually to zero.

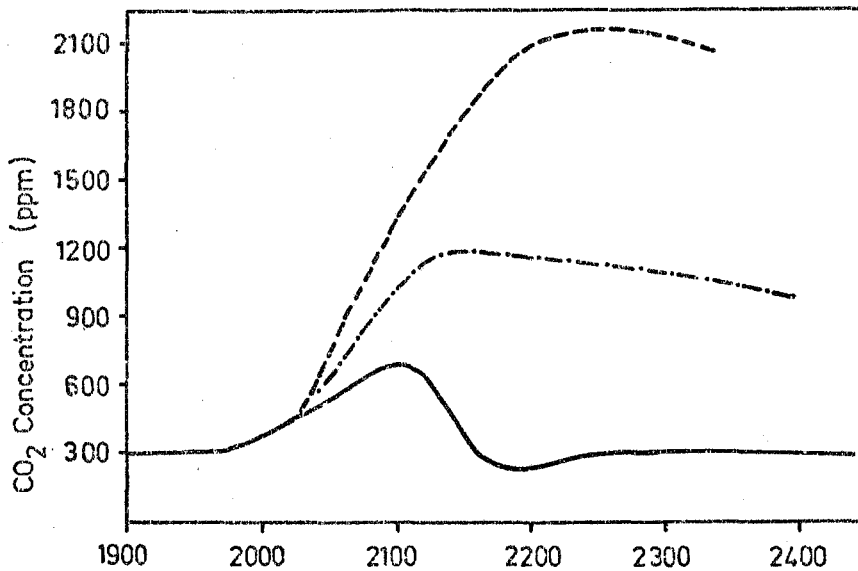


Figure 8b. Predicted increase of atmospheric CO₂ from 1975-2400 based on fossil fuel combustion as shown in a). The solid curve is obtained with an assumption of increasing land biota as dependent on atmospheric CO₂ (rate of increase 5 per cent of the atmospheric increase) and on size of the assimilating reservoir but no other limitations caused by other environmental factors. The dash-dotted curve shows a corresponding simulation when the assimilation rate increase is 30 per cent of the atmospheric CO₂ increase, but no increase of the assimilating portion of the land biota is permitted to take place 16. The dashed curve ignores the role of land biota 3.

Beyond this time any projection becomes considerably more uncertain. The most likely outcome would be a development somewhat less spectacular than the dashed curve in Figure 8, but above the dash-dotted curve.

6.2 Likely future changes of the nitrogen cycle

We first of all note the large reservoirs of fixed nitrogen present both in the soil (organic matter, 300 000 Tg) and in sea water (inorganic, 600 000 Tg, and organic matter, 400 000 Tg), in comparison with the annual turn-over in terrestrial and marine biota (about 2 000 Tg y^{-1} in each one). The annual natural fixation of nitrogen is more than an order of magnitude less, 140 Tg y^{-1} . Because of the much larger yields in agriculture that are obtained through use of fertilizers the present figure of 40 Tg y^{-1} fixation of nitrogen for these purposes may well increase by a factor of five or ten during the next fifty years, even though a very much more effective utilization of the nitrogen would be most desirable. The present world population needs only 6 - 9 Tg y^{-1} to have an adequate protein diet.

It is well known that the excessive use of nitrogen fertilizers may poison the ground water, but the inorganic nitrogen compounds are generally soluble in water and are fairly quickly transported to lakes and ultimately the sea. To the extent that increased production of organic matter takes place, this transit may be delayed. Denitrification processes may be enhanced and one can envisage that about one third of the nitrogen applied to the soil is returned to the atmosphere, i.e., at present 12 - 15 Tg per year 11. Maybe about 10 per cent will be in the form of N_2O . To the extent that such a relatively rapid return of fixed nitrogen to the atmosphere occurs, the impact on the atmospheric part of the nitrogen cycle may be significant at the turn of the century, i.e., a few per cent, and may increase further by a factor of five within 100 years 12. A global impact on the soil system and the marine biosphere on the other hand will hardly be detectable for several centuries, perhaps a thousand years. Significant local changes may be observed long before.

6.3 The response of the terrestrial and marine biota to a changing climate

Our knowledge of the likely changes of the biosphere that would be associated with climatic changes is essentially based on historical data, referring particularly to the period since the last glaciation. Experiments with climate models further show that the basic characteristics of the general circulation of the atmosphere remain about the same even under different climatic régimes. Features such as the middle latitude westerlies, the polar anticyclones in winter, the subtropical anticyclones or the intertropical convergence zone, however, change in intensity and position. To a first approximation (but see overview paper by Flohn) climatic changes may therefore be described as displacements of the present climatic zones, a description which accordingly also applies to the vegetation belts on land and to areas of intense primary production in the sea due to up-welling of nutrient-rich water. During the last glaciation Central Europe, which was just south of the ice sheet in Northern Europe, was covered by tundra, while the area around the Mediterranean had forests similar to those that we find further to the north today. Similarly the drought in the Sahel area in recent years may be described in terms of a southward displacement of the dry anticyclonic weather normally found in the Sahara.

It is important to emphasize that the decline and destruction of an ecosystem may be much more rapid than the development towards a climax, which only occurs gradually. It follows that a global climatic change will probably be associated with a decrease of the global primary production and, for example, a net return of carbon dioxide to the atmosphere, even though more productive ecosystems may develop in some areas. Most ecosystems are, however, quite resilient and climatic changes, like those that have occurred during the last few thousand years, have hardly had drastic consequences for existing ecosystems except in marginal areas. The advance of the desert northward in northern Africa during historic time is an example of quite drastic changes of biomes in such a marginal area.

Even if equilibria are not established quickly a first approximation of the changes of the land biota as a result of a climatic change can be obtained with the aid of diagrams such as those shown in Figures 2 and 3. It should be stressed finally, however, that the changing climate and associated changes of biota cannot be dealt with as one being a consequence of the other, since a mutual interplay takes place.

6.4 Does man influence the global climate by modifying the plant cover and soil structure on earth?

Man may modify ecosystems on land in two essentially different ways, by changing forests into agricultural land and by irrigation.

Local changes of the plant cover have only local effects on climate. These effects are much reduced by the exchange of air and energy with surrounding regions and last only as long as the modified land use is maintained by man. If man leaves the scene, the former conditions are restored fairly quickly.

The last two centuries have witnessed a very considerable expansion of agricultural land from about $8 \cdot 10^{12} \text{ m}^2$ to $15 \cdot 10^{12} \text{ m}^2$. This still only means an increase from 5 to 10 per cent of the total land area and an increase from 1.5 to 3 per cent of the surface of the globe. This expansion can hardly have been of much direct global influence on the climate, but possible associated changes of albedo and evapotranspiration may have had some regional consequences in the northern hemisphere. It has been suggested that overgrazing in quite large areas in the semi-arid zones of Africa may have had corresponding effects, but these have not been quantitatively established (see also overview paper by Hare).

Irrigation implies that water is being supplied more effectively for crop production. The prevention of surface run-off and the exploitation of groundwater reservoirs result in a reduction of the return flow of water from the continents back to the oceans. In the areas concerned, evapotranspiration is enhanced with direct implications for the energy budget. The albedo is usually decreased when more plants can grow, and more of the solar heat is thus converted into latent heat and transferred to the atmosphere. Local effects are obvious, regional effects possible but not established, global effects probably small or insignificant at the present level of irrigation, and will probably remain so for quite some time to come. Climate models may be used to assess more quantitatively the possible effects but their magnitudes are

probably too small to be firmly established in comparison with other effects not considered in these models at present or with such inherent features of climate as its random fluctuations in time and space.

Extensive irrigation may have an effect on lakes and possibly adjacent seas in the area concerned. One may for example ask the question what the implications may be of utilizing all run off from the surrounding countries to the Mediterranean, which is not an unlikely future development. If fresh water were only supplied by rain directly to the sea surface, the present balance with the Atlantic Ocean would be disturbed and a slow increase in salinity of the water might occur - a development that is well known for smaller water bodies in arid or semi-arid areas.

The most pronounced effects of man's interference with the global ecosystem, however, are probably the indirect ones via the global biogeochemical cycles, which have been dealt with previously in this overview.

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CLIMATIC VARIATION AND VARIABILITY:

Empirical Evidence from Meteorological and Other Sources

F. Kenneth Hare*

1. General statement of problem

This paper addresses the questions: Is there evidence that climate can and does change? If so, what do past records and present-day observations tell us about such changes? What is the nature of climatic variation and variability?

To the ordinary person, climate is the expectation of weather. The individual's plans are made on the assumption that weather through the year will proceed along familiar lines. Big day-to-day weather changes cause little trouble. But abnormalities as long as a season disrupt orderly planning, from private actions of individuals to the collective work of whole nations. Such abnormalities sometimes prolong themselves for years, or even decades. The Dust-Bowl period of the 1930s in North America and the Sahelian drought of 1968-73 in Africa were events of this sort. Both had disastrous consequences. Neither was foreseen. Urgent action to mitigate their effects could only be improvised.

In 1972 there were many such anomalies of climate, some of which had a major impact on crop yields, ocean fisheries, arctic navigation and the survival of flocks and herds. Since then several years have produced similar effects; drought, floods, extreme cold and severe storms have impressed themselves on the public memory. Widespread world anxiety has arisen from such questions. World food production and energy consumption, both in the course of rapid expansion, are seen to be especially sensitive to climatic variability.

If climatic impacts are to be combatted the world will need an accurate picture of climatic variation, as past records show it to be. Since detailed weather records are quite a recent innovation, however, only the most recent history of climate can be derived from direct measurement. In most countries little more than a century of records are available, and for many areas less than half a century. To go further back one must rely on proxy evidence, that is, on records of weather-related effects that have been preserved. These include, for example, tree-rings, pollen-sequences in bogs and lakes, ocean sediments, and even man's artefacts. This

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paper summarizes how these lines of evidence can be interpreted, and what they reveal about climatic variation and variability. More detailed discussions of past climates as such will be found in the overview papers by Gerasimov and Flohn.

The study of climatic history is valuable because what has happened in the past may well happen again. Climatologists have to learn from past events, as do economists, historians and biologists. The unheralded event - unprecedented in history - is highly unlikely; but it may still happen. The reconstruction of climatic history gives us an informed perspective, a set of yardsticks against which to estimate what the future may hold.

2. Character of climate and climatic variation

In scientific terms climate is the generalization of atmospheric behaviour over some arbitrary reference period longer than a few weeks. Most authorities would, indeed, say longer than a few years. Reality consists of the endless succession of individual weather states. We seek, however, to get a mental grasp on this succession by defining the climate, usually choosing the following sorts of measure (see Figure 1):

- (a) estimates of the average values, or central tendencies, of the more important climatic elements, such as temperature and precipitation;
- (b) estimates of the characteristic kinds of variability about these averages. Such variability includes:
 - (i) periodic effects, defined in terms of frequency (or period) and amplitude, such as those connected with day and night, or winter and summer;
 - (ii) quasi-periodic effects, which tend to recur at approximately the same frequency or period (for example the monsoonal rainy seasons, or the sunspot cycles); and
 - (iii) non-periodic effects, such, for example, as those that display themselves between successive days in the week, or between years in the decade.

Periodic phenomena reproduce themselves regularly, and have a predetermined period and phase (though not always amplitude): quasi-periodic phenomena are less regular, and generally represent characteristic response or relaxation times for processes that are not really periodic.

Before the question of possible climatic change arose, climatologists adopted the practice of forming the above estimates for thirty-year reference periods. These were recalculated every ten years (e.g. 1931-60, 1941-70 etc.). It was found that small differences occurred between these successive reference periods. Such differences are bound to occur because of the extremely variable character of the climate's behaviour. They can be thought of as climatic noise, and their occurrence does not indicate a real climate change. Climatic variability is treated in this paper as the

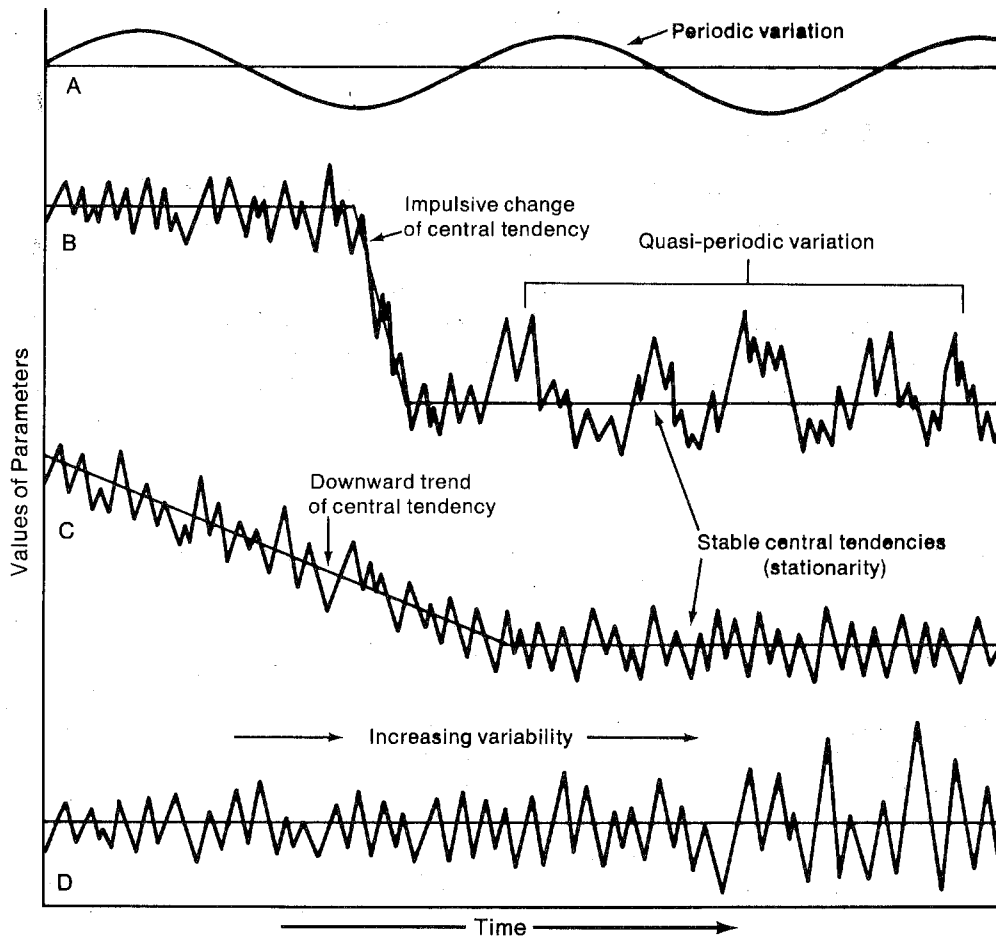


Figure 1. Sketches of classes of variation and variability, to show usual meaning of terms used in text.

internal variability characteristic of the reference period. It is made up of the components described in the above paragraph. Such variability is a fundamental part of climate, and has a high economic impact. It will be treated in detail later in this paper.

But the major question before the Conference is the possibility of real climatic variation, or change (the latter term being applied, as a rule, to larger, longer-term variations for which a definite cause can be assigned). Such variation or change will show itself as real differences between reference periods, larger than those associated with climatic noise. The main problem is to find evidence for such variation. It is generally slow and hence its effects are of small magnitude in the short term. The noise is likely to mask it. It is all too easy, in fact, to mistake the noise for evidence of real variation; the great variability of climate may well mislead the public into thinking that real variation is in progress. For example, a severe summer drought - without precedent, perhaps, for two or three centuries - may be part of a real variation towards a drier climate. But it is more likely to be part of the variability of the existing climate, and hence not a sign

of any real shift. One must be cautious before one concludes that a variation of climate is in progress.

3. Weather and climate

Weather in middle and high latitudes of both hemispheres is produced by the evolution and motion of disturbances of the dominant westerly currents. These disturbances are the cyclones and anticyclones - highs and lows - of the daily weather map, which bring the familiar succession of dry and wet days, clear and cloudy skies. Such systems are born, amplify and usually decay within a few days. In some areas, such as the oceanic sub-tropical latitudes of both hemispheres, the life of individual weather systems is much longer. But the basic principle that weather systems decay, and live at most only a few weeks, is fundamental. Even within the tropics, where travelling cyclones and anticyclones do not dominate events, the time-scale of weather is short.

The distinction between weather and climate is important. The atmosphere's behaviour, though endlessly variable because of such disturbances, is not random. Events do not follow one another in an uncorrelated, meaningless way. They display persistence, as random processes do not. Even so the atmosphere's memory often appears short. Figure 2, for example, shows (for middle and high latitudes of the northern hemisphere) the time in days believed to separate effectively independent (i.e. uncorrelated) values of sea-level pressure 1, 2. In the disturbed mid-latitude belts of North America and East Asia, pressure charts less than 3 or 4 days apart are effectively independent. From mid-Atlantic across the pole to the east-central Pacific, the period needed to separate independent charts is longer - of order 5 days in summer, and 6-8 days in winter. Even the longest of these periods, is, however, short in comparison with the time scale for consideration of climate.

If one now examines much longer observational records (time-series), one finds that for periods beyond those shown in Figure 2, the annual cycle appears to dominate events even in the humid tropics. The seasons are very much part of the climate. This is a truly periodic effect, dictated by the orbital movement of the Earth round the sun, and the tilt of the Earth's axis.

Beyond the calendar year, there is another and still unexplained tendency for events to recur every 2 to $2\frac{1}{2}$ years, the so-called quasi-biennial cycle. This tendency affects many rainfall records and dominates stratospheric winds in low latitudes. It is a quasi-periodic effect, meaning that events have a tendency to repeat themselves at about this period. Beyond that, and out to two or three decades, there is a range of period in which there seems to be little tendency towards such periodic or quasi-periodic effects (see overview paper by Oguntoyinbo and Odingo).

For periods of three decades or more, however, and right out to thousands of years, the available proxy records consistently show more tendency towards quasi-periodicity than one would expect from random effects. Climate seems to contain repetitive effects on all time-scales beyond a few decades, though non-periodic phenomena often conceal them. The biggest of these effects seem to be those associated with very long-term changes, for example the sequence of glacial and non-glacial conditions we associate with periods of about 100 000 years 3, 4, 5.

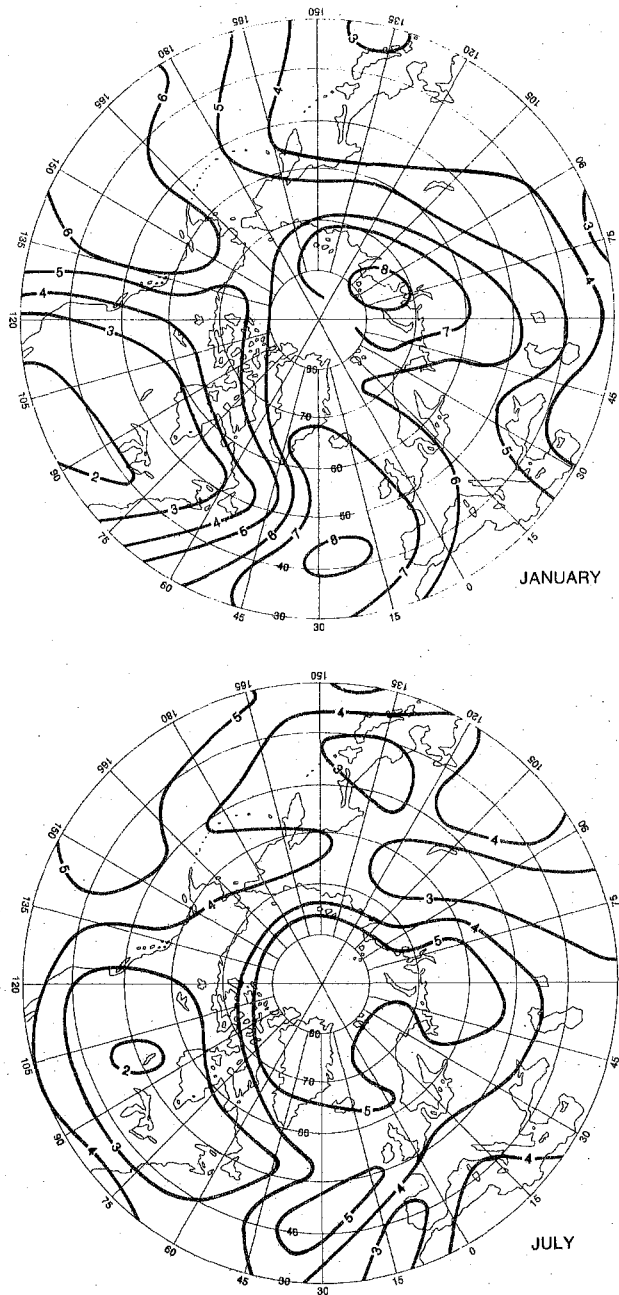


Figure 2. Period in days required to separate effectively independent values of sea-level pressure (using Leith's criterion). Clearly the atmospheric weather "memory" is shortest over North America, where day-to-day changes are large and rapid, and longest in eastern oceanic sectors and the Arctic 1, 2.

Hence a full knowledge of what climate can do (because it has done so in the past) requires historical information going back many millennia. This is so far beyond the time-scale of politics and economics that to include it here may seem absurd. But such is not the case. The present non-glacial epoch of world climate has lasted 10 000 years, as have civilized modes of life. There have been previous warm epochs that lasted no longer than this. We have no guarantee that our own epoch will do so, and the possibility of a new ice age has been widely discussed by the world's public. As other overview papers will show, there is a possibility that the very reverse - a marked warming - will be induced in the next two centuries by human interference. Clearly one needs to judge such hypotheses against climate's long-term performance. Climatic history on the 10 000 year scale and longer is therefore relevant to present-day concerns.

4. The climatic system

The idea of climate just put forward concerns only the atmosphere. But climate is clearly part of a bigger system. Oceans, lakes, soils, glaciers, plants and animals all have an internal climate, and all interact vigorously with the atmosphere, whose behaviour is thereby altered. The climatic system is the term applied to this complex set of processes and interactions. Bolin's overview paper (on global ecology and man) will focus on the biota (the set of living organisms in the system) and its interaction with atmospheric climate. The term ecosystem is applied to the biota and its interaction with its physical environment, including the atmosphere. Obviously climatic system and ecosystem are related but different ideas.

The variability of the climatic system is substantially lower than that of climate itself. Each of the other components of the system is more constrained than the atmosphere. Each takes longer to adapt to a change of external stress. Each has far slower internal processes. The net effect is to apply a brake to the atmospheric climate, whose extreme variability is thereby reduced. The ocean in particular is a more sluggish body than the atmosphere, besides being a more capacious store for water, carbon and many other trace constituents. It responds more slowly to all kinds of external influence. Air-sea interaction is a key climatic process.

Much of the evidence for past climates comes from these more conservative parts of the climatic system. The proxy data on which we depend are derived very largely from the ocean floor, lake bottoms, glaciers, bogs and trees. In effect, we rely on the ability of these reservoirs to yield a record of their own past interactions with the atmosphere. Fortunately, they have a far longer memory.

5. Former climates

5.1 Ancient climates (more than 2 million years back)

Little is known about the climate of the Earth prior to the past two million years. The available evidence is well summarized elsewhere 6, 7, 8. It is derived largely from the study of continental rocks, whose ages range back several thousand million (10^9) years. The sedimentary rocks in this long record show that there has been liquid water on the Earth's surface for at least 3.7×10^9 years. The kinds of

sediment accumulating in these waters slowly changed as the Earth's atmosphere evolved and as life appeared on the land surfaces 9. On the other hand there were at least three periods of prolonged glaciation, when polar temperatures were low enough to allow the accumulation of ice sheets like those now engulfing Greenland and Antarctica. The earliest proven instance of such glaciation was about 650 million years ago. The present ice age, in other words, had several predecessors, though ice was almost absent from the Earth for much of geological history (see overview paper by Gerasimov).

Interpreting this evidence has many pitfalls. The distribution of oceans and continents, for example, has drastically altered. Only during the past 20 million years has the Earth's map been much like that of today. It is also clear that the Earth's atmosphere has undergone changes of composition. The probability, nevertheless, is that the surface temperature of the Earth (at present near 288 deg K or 15 deg C) has not greatly changed over a period of 2×10^9 years. Figure 3 shows a recent model calculation of surface temperature 10 that takes account of:

- (a) changing carbon dioxide and water vapour content in the air;
- (b) the influence of a probable slow increase in the solar constant;
- (c) changes in day length due to the moon's capture about 4×10^9 years ago.

Such analyses are sketchy and approximate, but they suggest that the present-day Earth's surface (and that of the past two million years) are substantially cooler than has been usual in history. We live in an abnormal phase of a planetary climate that in most epochs permitted a largely ice-free surface. Nothing in the record suggests that we are about to climb back to the normal condition which may well be 5 to 10 deg C warmer than present conditions.

Man's entire evolution as a species took place during this cool phase of Earth history. The cooling began in early Tertiary times (about 50 million years back) culminating in the series of glacial and interglacial epochs of Quaternary times, from which we have not emerged. Our history as a labour-dividing, civilized society has taken place within one single interglacial epoch, the past 10 000 years. Though one cannot say deterministically that we are the product of this anomaly, it has profoundly influenced our behaviour, our economy, and perhaps even our physique.

5.2 The Quaternary Period (the past two million years)

In this more recent part of the geological record, we can draw on a richer record to extract proxy evidence of climatic variation. The sorts of evidence used include 6:

- (a) the kinds of sedimentary rocks, made easy by the highly distinctive nature of glacial deposits and associated lacustrine materials;
- (b) the chemistry, fossil organisms, and oxygen-isotope ratio of oceanic sediment cores;

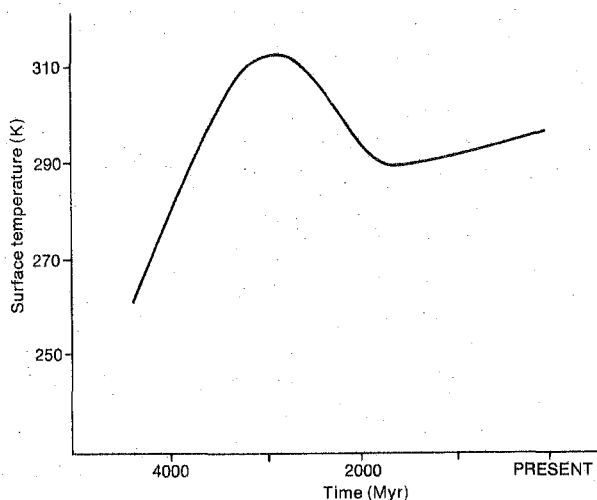


Figure 3. Estimated surface temperature of the Earth during geological history from model calculations [10].

- (c) the oxygen-isotope ratio of glacial ice;
- (d) the fossil pollen assemblages from lake and bog sediments;
- (e) many aspects of the distribution of plants and animals, now and in the past.

All these types of evidence need to be supplemented by suitable dating techniques.

As an example of the use of proxy data we can consider the case of deep sea-cores. In one such core from the equatorial Pacific [11], the sediment accumulated at the rate of 1 cm per millennium, in still, undisturbed conditions. The core can be read as a crude thermometer of sea-surface temperatures throughout the 2 million years it represents (the entire Quaternary period), by means of the ratio of oxygen isotopes, ^{18}O to ^{16}O , in the shells of micro-organisms.

Such records show that during the past 2 million years the world has passed through a series of glacial epochs with shorter, warmer interglacials in between. Particularly since about 450 000 years ago, each glacial epoch has ended in an abrupt warming, probably of order 5 to 10 deg C. There have been five such interglacial epochs since 450 000 years ago, counting our own, which is already 10 000 years old. There were four intervening glacial epochs. The terms glacial and interglacial are relative, since it is unlikely that either hemisphere has ever been totally ice-free during the past million years. The Arctic Ocean has probably never lost its pack ice cover, and the Antarctic continent has been ice covered much longer, probably for 11-14 million years [12]. The interglacial climate so familiar to us is only a partial recovery towards geologically normal conditions.

The past 150 000 years are known with more precision, thanks mainly to studies of ice volume and pollen analysis. Pollen is chemically almost indestructible, and its slow accumulation in growing bogs or accumulating lake sediments enables us to reconstruct the kinds of vegetation that flourished in the surrounding areas. A picture of the climate can hence be derived, either qualitatively or by means of mathematical transfer functions. Fairly accurate dating can be achieved for the final 50 000 years using carbon-14 methods. Less exact techniques can be used to complete the dating.

Figure 4 shows, in simplified form, the longest continuous record obtained in this fashion 13. It comes from the Vosges Mountains in eastern France. The core goes back an estimated 140 000 years, and shows the record of the final glacial epoch, the preceding interglacial, and traces of the penultimate glaciation of the region. Alongside it is a record from Camp Century, Greenland, showing for a comparable period the oxygen-isotope anomaly in the ice. Both show the abrupt end of the last glacial epoch about 10 000 years ago.

These repeated changes over two million years created great stress among living things, especially on land in the northern hemisphere. The temperature changes were greatest in high latitudes, as they are today. The forests, grasslands and animal populations were repeatedly forced to migrate, as the glaciers waxed and waned. We know that there were changes, too, in the deserts of the sub-tropics. Only the equatorial environments maintained relative constancy, and even there fluctuations of temperature and precipitation occurred.

Inevitably the bulk of the evidence has come from the northern hemisphere, and we are not certain that the two hemispheres always marched in step - though on theoretical grounds we should expect them to do so. The growing weight of evidence from deep cores from the Southern Ocean, however, has virtually clinched the argument in favour of simultaneity. The glacial and interglacial epochs were roughly simultaneous in the two hemispheres.

The most convincing evidence that this is so has come from the CLIMAP project, which is a many-sided attempt to map the climates of the past. A recent CLIMAP study 14 has analysed the contents of two 450 000-year ocean cores from the Southern Ocean, south-west of Western Australia. The analysis gives evidence of the volume of northern hemisphere land ice, sea-surface temperatures in the sub-Antarctic, and of Antarctic surface water structure. The records indicate that the major changes affected both hemispheres. They also indicate that these changes were quasi-periodic, leading the authors to refer to Earth orbital changes as the pacemakers of the Ice Ages:

- (a) the dominant period of variation of composition in the cores was near 100 000 years, correlating closely with the periodic variation in eccentricity of the Earth's orbit around the sun. The main glacial epochs coincided with intervals of low eccentricity;
- (b) other periods of variation in the cores were approximately 40 000 to 43 000 years, corresponding to the period of the obliquity of the polar axis; and 19 000 and 23 000 years, which are related to the precession of the equinoxes.

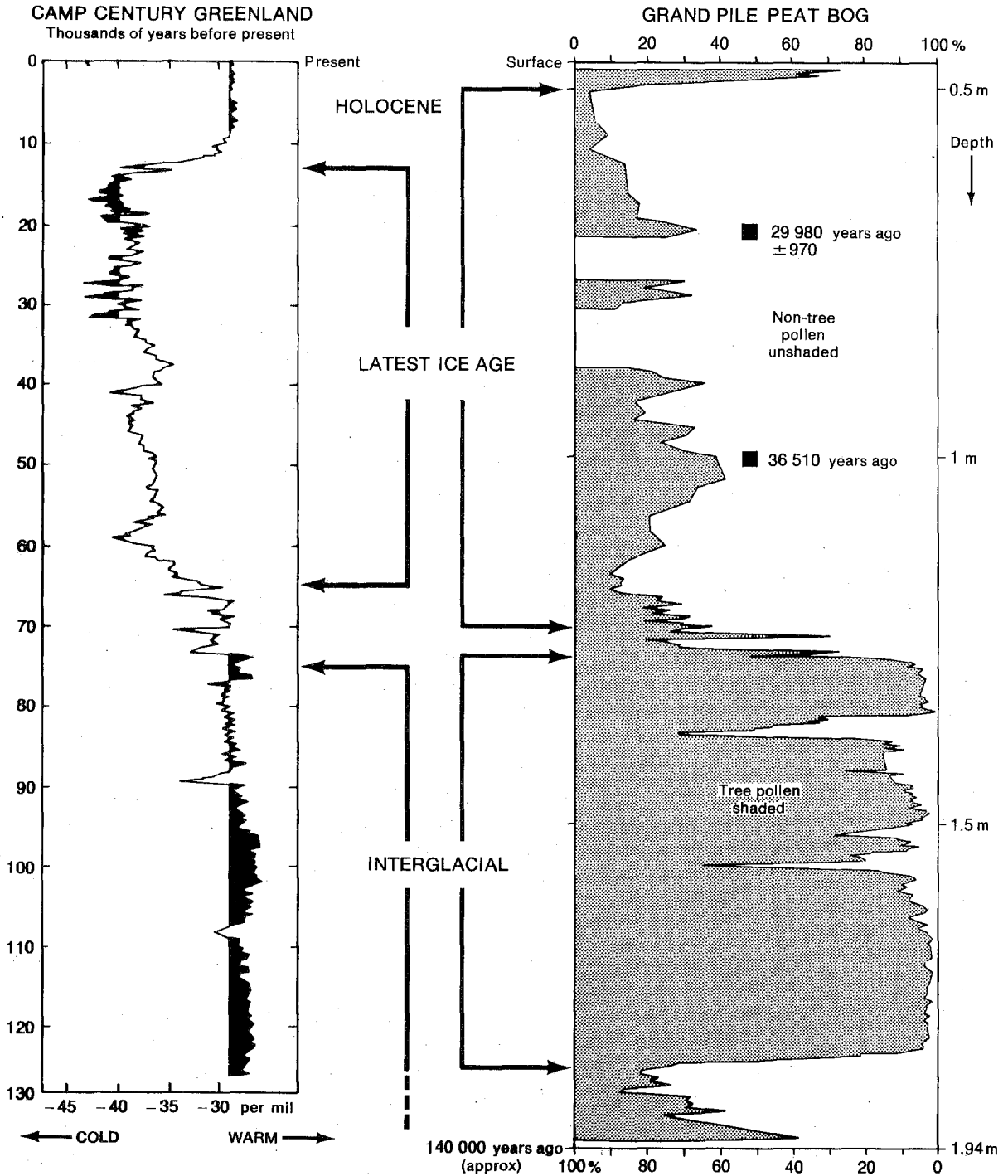


Figure 4. Variation of mean surface temperature during the past 140 000 years from two temperature-sensitive proxy sources. The curve on the left, from a core in the Greenland Ice Cap, shows variations of the oxygen-18 to oxygen-16 ratio as a function of calculated date, in thousands of years before present. [6]. The curve on the right, on an approximately equivalent scale, shows tree and non-tree pollen from a 1.94 m deep core from the Grand Pile peat bog, Vosges Mts., France, estimated to cover about 140 000 years of accumulation. Radiocarbon age determinations are given for two levels [13]. The two curves cannot be matched exactly because of variations in accumulation rate, but both clearly show the final glacial epoch separating the warm Holocene from the previous interglacial (during which there were two brief cold episodes).

These results - that the alternation between glacial and interglacial climates has a period of about 100 000 years - present a puzzling physical problem. The eccentricity has a very small (of order 0.1 per cent) effect on the amount of solar energy reaching the earth, whereas the obliquity redistributes the energy significantly - and should have more climatic impact. A recent study [15] shows that the last ice sheets reflected this influence. Between 83 000 and 18 000 years ago (the period of glaciation), the solar radiation reaching the Earth north of 45°N was roughly 19×10^{25} J less than normal, whereas in the period 16 000 to 6 000 years ago (the ice waning phase) there was an excess of 4×10^{25} J, in both cases due to the orbital variations. Each increase due to the 43 000 year period was accompanied by a significant ice retreat - and this included the final spectacular decline of the ice sheets about 10 000 years ago. The 40 000 to 43 000 year period therefore appears to play a key role, even though the major climatic changes occur on a 100 000 year period.

So much evidence has now accumulated from ocean areas that an attempt has been made to draw maps of sea temperature from 18 000 years ago [16], with some crude detail of continental surface conditions - though the lack of firmly dated material on land handicaps the latter (Kutzbach, personal communication). On the basis of this reconstruction, large-scale mathematical models of the atmospheric circulation of the time have been developed [17, 18, 19]. Such experiments are of great value in extending our understanding of these major climatic variations of the past, but they have still to be regarded as tentative.

5.3 The Holocene epoch (the past 10 000 years or so)

The withdrawal of the final ice-sheets from Europe and North America was achieved quite quickly (Figures 5 and 6) [20, 21, 22]. The coming of a new interglacial epoch - our own times - was, as usual, quite sudden. There was a large and rapid rise of temperatures, and by 7 000 years ago the world was a degree Celsius or so warmer than it is today (with wide variations). This early Holocene warming was accompanied in many parts of the world by some increase in precipitation, especially in the sub-tropical deserts of the northern hemisphere (see overview papers by Flohn and Gerasimov).

Thereafter, beginning a little before 5 000 years ago, a series of changes ensued that led for the most part towards less favourable conditions. In northern Canada and Alaska, for example, there was a retreat southwards of the northern limit of trees. Dead stumps still litter the surface of the tundra that has prevailed ever since. A significant cooling began about a millennium later across much of Eurasia. Reported changes in the southern hemisphere were, however, smaller, and less consistent in sign.

From the standpoint of this Conference the most significant mid-Holocene changes were those that occurred in and around the sub-tropical deserts of the northern hemisphere, especially the Sahara, the Arabian desert, and the Indus Valley-Rajasthan area. From reconstructions by many workers [23, 24, 25, 26, 27, 28], it is clear that much of the sub-tropical dry belt, from west Africa to Rajasthan, was wetter between 12 000 and 4 000 years ago than today, with some less humid phases [29]. Extensive savannah grasslands existed in parts of the Sahara, and many African lakes (some now dry) stood at high levels. Rajasthan and the Indus Valley precipitation was at times more than double its present value.

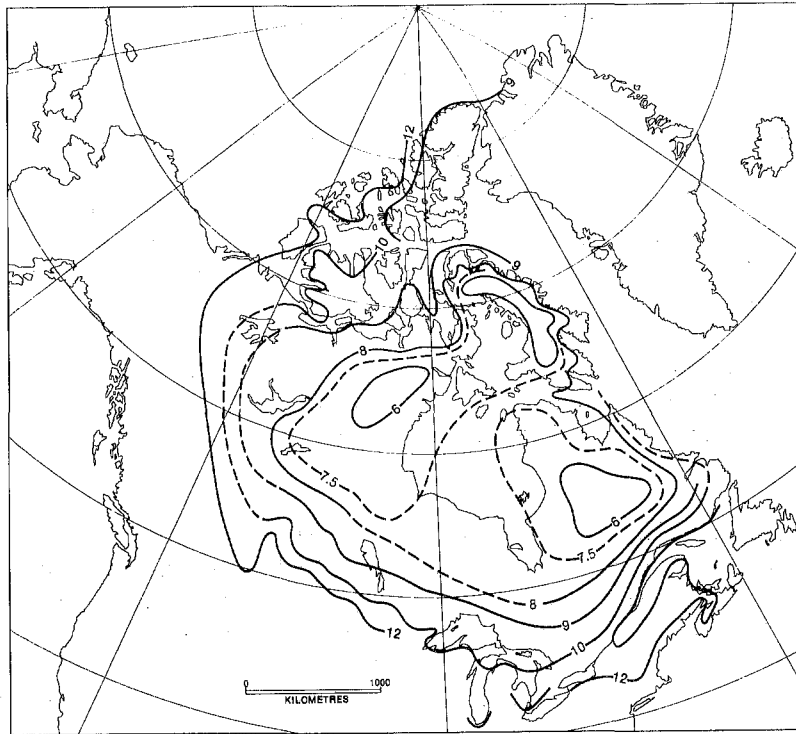


Figure 5. Date (in thousands of years) of oldest known organic materials formed on deposits left by the retreating Laurentide ice sheet of late Pleistocene times, based on carbon-14 dating. The retreat of the ice was rapid in early Holocene times. Final dispersal was accelerated by invasion of Hudson's Bay by the sea after 8 000 BP 20.

These more humid conditions permitted early man to flourish as a hunter of big game in regions now utterly desert. The hunters of the Saharan steppes and savannahs left an extraordinary pictorial record of their prey in the form of cave and cliff paintings. In the Indus Valley civilizations arose that rivalled those of the Middle East, at Harappa and Mohenjo Daro. In Australia, however, where the early Holocene moist phase may have been shorter and more intermittent, no such cultural change occurred. The aboriginal peoples survived with little alteration in life style into our own century 30.

In the past 4 000 years desiccation has predominated in much of the subtropical belt, and these favourable environments have been slowly destroyed. Rainless desert, with active sand dunes in many areas, covers today what were once productive lands. The process has not been continuous, nor has it been simple. In the Sahara it has affected both the northern flank, which is fed by winter rains, and the Sahel on the south, which gets rain only from the summer monsoon. Figure 7 shows the dramatic effect in the Rajasthan desert. The Indus civilizations were eclipsed by this desiccation.

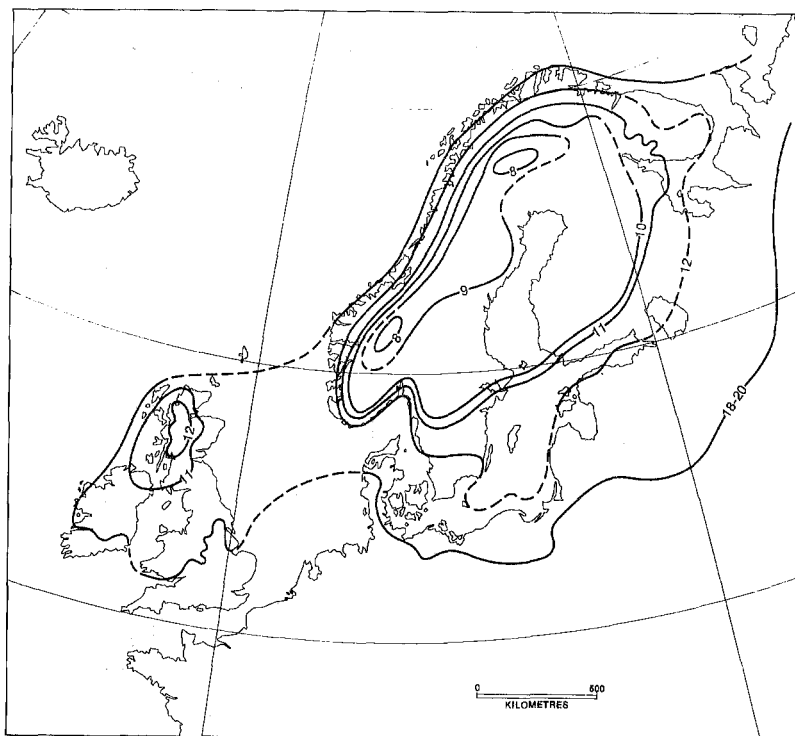


Figure 6. Similar to Figure 5, but for north-west European ice sheets 21.

The mechanics of these changes is not yet understood. Almost certainly they were related to major changes of the general circulation of the atmosphere. But in the case of the desert margins, it may well have been that the work of man assisted the process. By overpasturing or overcultivating the vulnerable soils, he may have set in motion feedback processes that intensified the tendency towards a drier régime.

Our own millennium has continued the instability. We can add annual tree-ring records and historical evidence, since written documents attest to many of the effects. Most noteworthy of the variations were:

- (a) an early mediaeval warm phase (800-1200 AD) which left many northern shorelines ice-free, and permitted the Norse voyages to North America, and the colonization of Iceland and Greenland;
- (b) the "Little Ice Age", between 1550 and 1850 AD, a sharply cooler (of order of 1.5 deg C) period of harsh winters and shortened summers in North America, Eurasia and (more locally) in temperate latitudes of the southern hemisphere 31.

These variations were small, yet they had major economic and political impacts. The Norse navigators could not press home a colonization of North America after 1200 nor could they retain the Greenland settlement (though non-climatic factors were at work as well). Iceland survived the Little Ice Age with difficulty, and its scholars

have presented us with the most comprehensive records of the battle against climate. European vineyards waxed and waned in prosperity and extent as the climate varied.

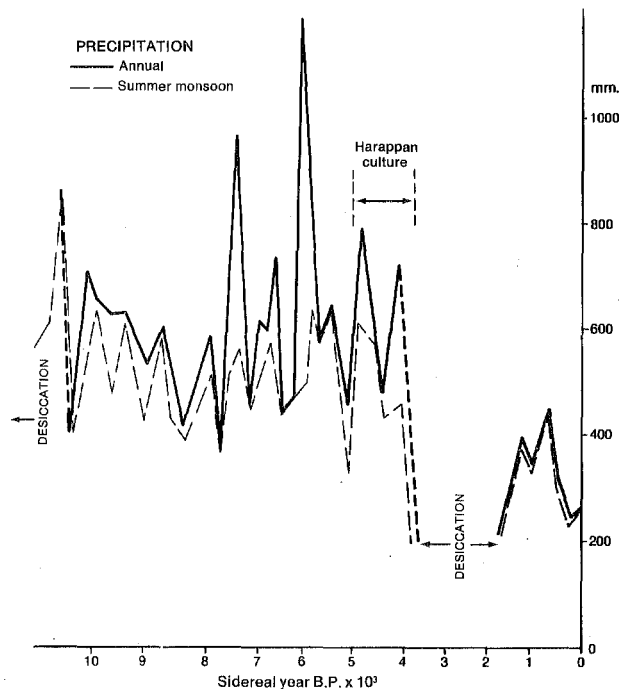


Figure 7. Estimated precipitation, from lake levels and other evidence, for past 11 000 years in Rajasthan, showing sharp desiccation culminating about 3 700 BP. Abscissa time-scale is irregular to allow for corrections to radiocarbon time-scale used in original plot 27.

Overall, the late Holocene climates were clearly much like our own in general outline. Even the slow desiccation of the sub-tropics has a familiar ring today. The period took mankind from the age of dynastic Egypt, Sumeria and Akkad into the technological civilization of the 20th century. Without doubt the spread of man's influence had some climatic impact, especially in the sub-tropics. But the general pattern of climate has persisted, and we can progress into a discussion of present-day variations without any drastic change.

6. Recent climatic variability and variation

6.1 The observational base

Although some instrumental observations of weather date back to the seventeenth century, effective observation of surface climates really began little more than a century ago. At sea the coverage was and remains largely confined to the main navigation lanes. In the post World War-II era, we began to have access to frequent soundings of temperature, pressure and humidity from radiosondes (which transmit observations by radio to ground receivers). From the mid-1950s onwards a reasonable

world distribution of such upper air soundings has been available on a twice-daily basis, with penetration upwards to 30 km or higher, and with direct wind measurements at many points. We are now in the midst of a revolutionary change towards satellite-borne sensors that have already provided the first world-wide coverage of such elements as cloudiness and infrared radiation from Earth to space. Rapid further development of such remote sensing devices will transform the study of climate, though this will require what is not so far available - an effective way of storing the huge amounts of new information being received continuously.

6.2 Trend of mean temperatures since 1880

Figure 8 shows an estimate for the past century of the variation of mean surface air temperature in the northern hemisphere [\[32\]](#). The values are unsmoothed, so as to emphasize interannual variability. The average (root mean square) deviation of annual hemispheric temperature from a smooth trend line drawn through the data is about 0.2 deg C. The trend clearly reversed during the century. Temperatures rose about 0.6 deg C by the late 1930s - with 1938 the warmest year. They have since fallen by about 0.4 deg C. At the end there is a suggestion that the fall ceased in about 1964, and may even have reversed [\[33\]](#).

Figure 9 challenges the view that the fall of temperature has ceased [\[34\]](#). These curves begin in 1950 or later. They include many more surface data, and are spatially more representative. Parameters include surface air and sea temperatures, the mean temperature of the lower atmosphere, and the extent of snow and sea-ice. Except for the north polar belt, the northern hemisphere has continued its cooling during the 1970s. In particular 1976 [\[35\]](#) was exceptionally cool. A marked increase in winter snowcover (chiefly in Asia) that began in 1971-72 [\[36\]](#) and then reversed itself a little in 1973-74, has become even more noticeable.

Although authorities differ in their interpretation of this evidence - some being still inclined to say that the northern hemisphere ceased to cool about 1965 - the weight of the evidence clearly favours cooling to the present date. This cooling is true even of the well-monitored parts of the ocean surface. The striking point, however, is that the interannual variability of world temperature is much larger than the trend. Especially in high latitudes differences from year to year are striking. Hence it is difficult to detect a genuine trend. Obviously variability, as defined in Section 2, exceeds variation, or long-term change.

It is questionable, moreover, whether the trend is truly global. Calculated variations in five-year mean air temperature over the southern hemisphere [\[37\]](#) chiefly with respect to land areas, show that temperatures generally rose between 1943 and 1975. Since the 1960-64 period this rise has been strong (Figure 10), especially in high latitudes. The effect is most pronounced in the Australasian sector of the hemisphere. Hence, the scattered southern hemisphere data fail to support a hypothesis of continued global cooling since 1938. The question remains in doubt.

If these effects are real, and if sea surface temperature tends to vary with the same sign as the atmosphere, the small changes in the hemispheric temperatures must be due mainly to changes in the overall heat exchange with space. If the

hemispheres vary with opposite signs (as they may have done between 1943 and 1975), the changes may be due in part to exchanges of heat between hemispheres. The accuracy of the estimates does not allow us to decide between these or other possibilities.

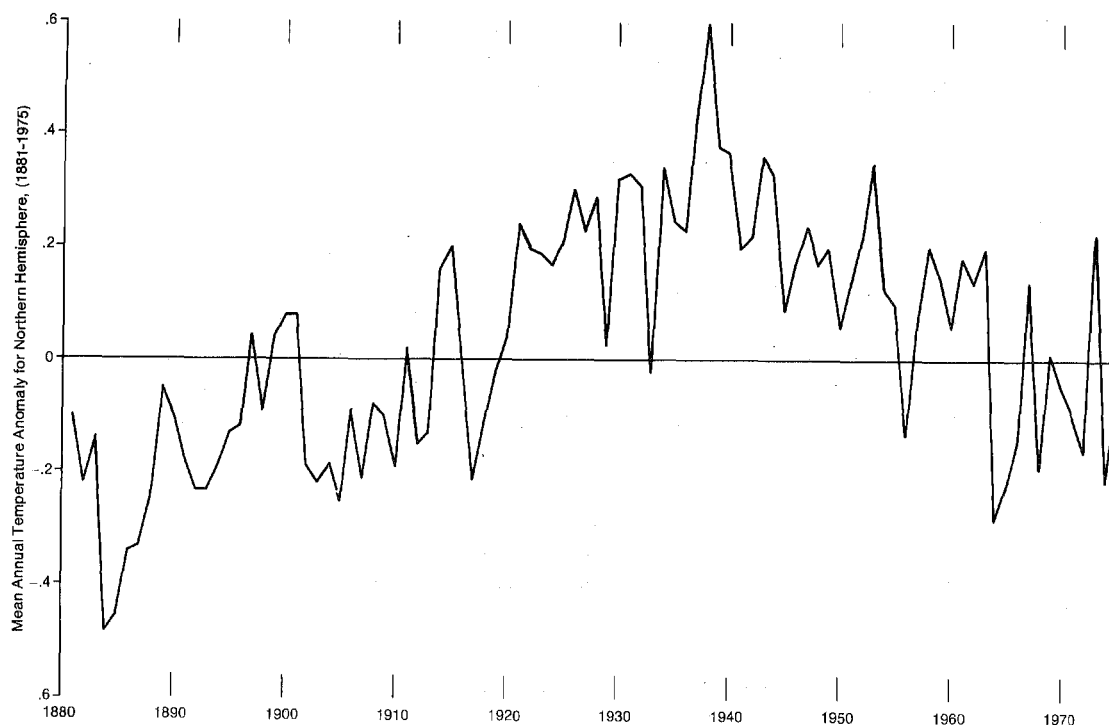


Figure 8. Mean annual surface air temperature over northern hemisphere, 1881-1975, as deviation from period mean 32.

The small hemispheric or global changes are actually insignificant by comparison with the large spatial anomalies that have been demonstrated 38. During this century there have been prolonged and persistent spatial anomalies much larger in magnitude than the hemispheric trends discussed above. Successive 15-year periods show very large anomalies that may reverse in sign between periods (Figure 11). Thus 1940-54 saw moderate to strong rises of winter temperatures over the United States and much of Europe. The period 1950-64, overlapping the first by five years, saw strong cooling in the same areas. The areas of high temperature on these charts were areas with an unusual strength of persistence of southerly wind anomalies, whereas the areas of cold were related to outflow from high latitudes. In other words, the thermal anomalies were of advective origin.

In brief, the apparent trends visible in Figures 8, 9 and 10 are actually dwarfed by comparison with typical interannual changes, and with spatial anomalies that may persist for more than a decade. Both types of variability trace back to the same causes - abnormalities of winds or of ocean currents, which redistribute the available heat unequally. These variabilities are at present of greater economic importance than the slow trends that are visible in the data. Most economic losses

due to climate can be traced back to such protracted anomalies of atmospheric and ocean circulation patterns. Especially important is the unequal way the anomalies affect regions of the world: losses in one area may be accompanied by gains in another. However, Swaminathan in his overview paper, suggests a tendency towards positive spatial correlations of crop yields.

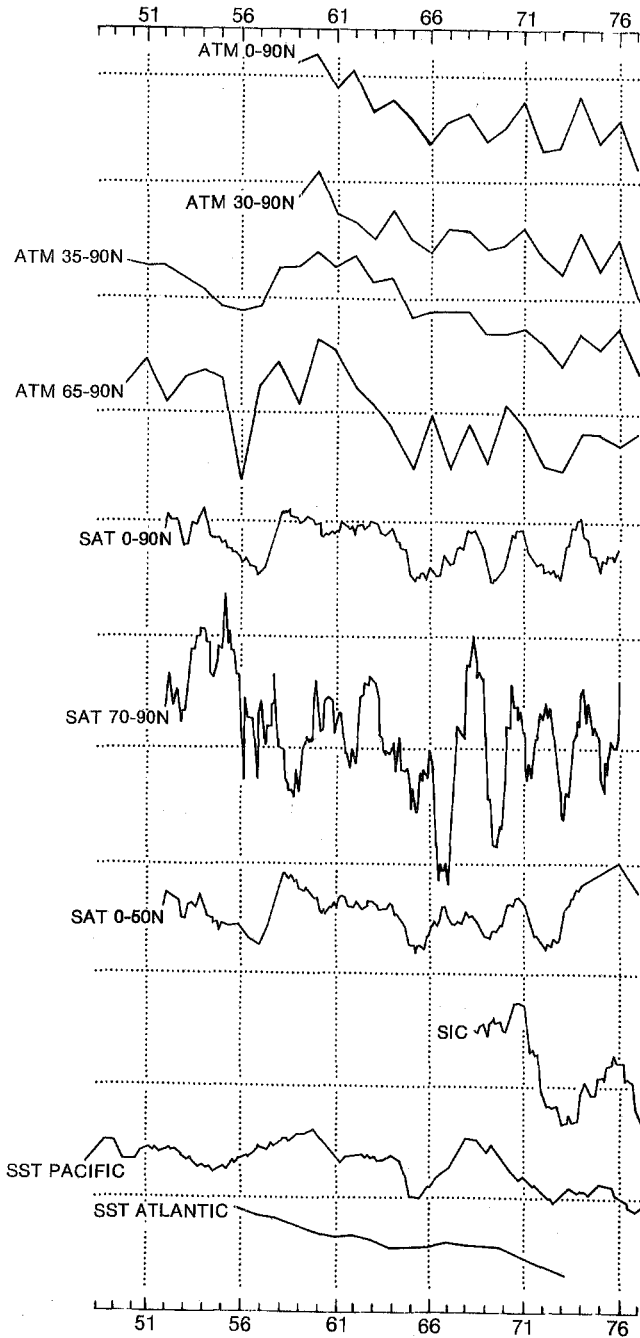


Figure 9.

Selected temperature and other curves for the northern hemisphere since about 1950, for specified latitude bands and following domains: ATM, atmosphere, surface to 100 mb; SAT, surface air temperature; SIC, sea ice extent; SST, sea surface temperature. For the temperature curves, no absolute scale is shown, but distance between successive dotted ordinates represents a degree Celsius 34.

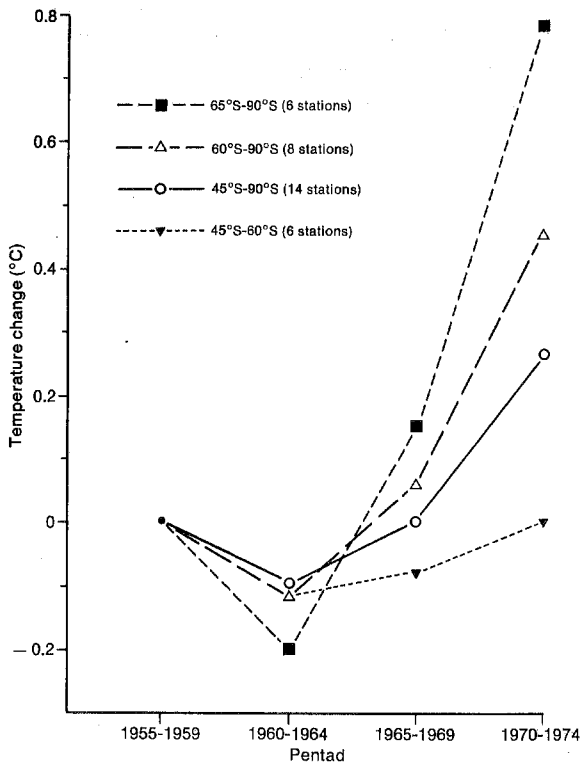


Figure 10.

Variation of mean surface air temperature since 1955 over various groups of middle and high latitude stations in the southern hemisphere [37].

Nevertheless the trends will ultimately affect the human economy, if they continue, or if they reverse and then endure. A cooling of 0.2 deg C per decade would reduce world temperatures by 1 deg C if it continued for 50 years (i.e., to about 2027). This would be quite enough to have an adverse impact on northern agriculture. It might affect warm temperate agriculture beneficially, since many crops are grown above their optimum temperatures. There might also be associated changes of precipitation. On the other hand, if the trend reverses because of carbon dioxide heating (see, for example, the overview papers by Flohn, Mason, Munn and Machta, and Bolin), it will also create economic impacts. We conclude that temperature variability has much greater present impact than that due to long-term trends, but that such trends must be watched with the utmost care. In the long run they may drastically affect the human economy.

6.3 Is variability of temperature increasing?

The vital importance of temperature variability is easily demonstrated. Much less easy to decide is whether the variability changes with time. It is actually made up, as shown above, of different components. Some portion is due to purely periodic forcing by the sun, as is clearly the case with the daily and seasonal changes. Another portion may be due to longer-term quasi-periodic variations having to do with characteristic exchange times between air and sea, or to other quasi-periodic effects not yet demonstrated. But much of the variability arises from the prolonged circulation anomalies described above, and these are mostly non-periodic.

Detailed knowledge of temperature variability is available over too short a period to sort out these possibilities.

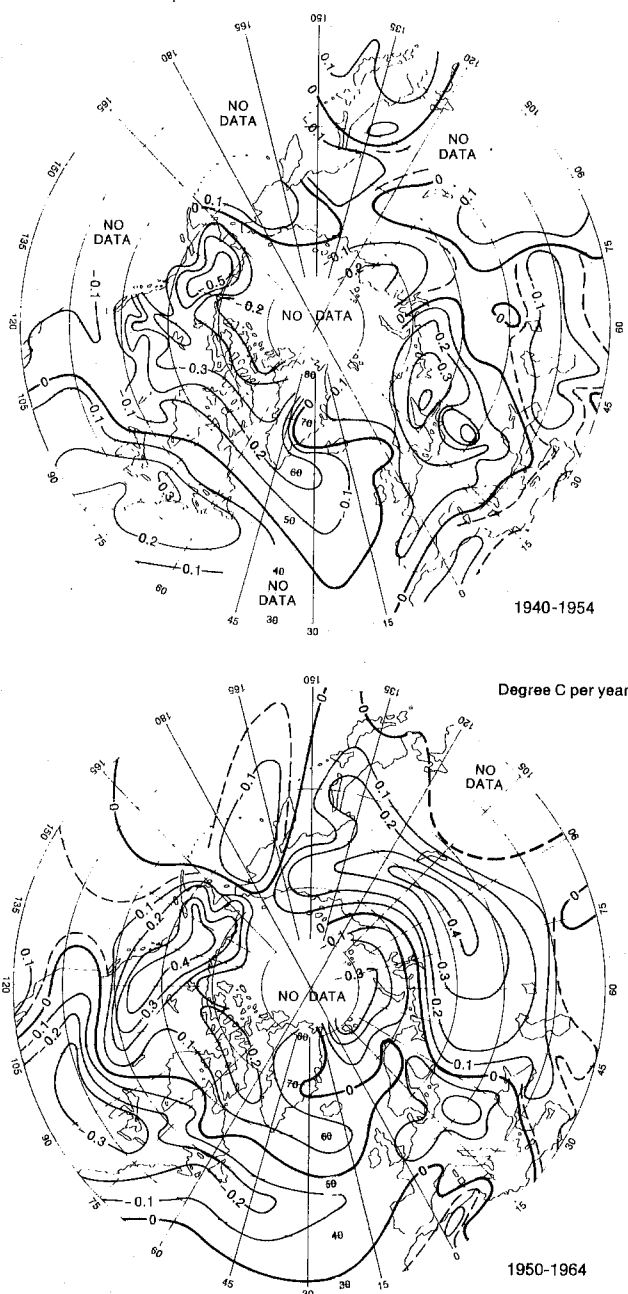


Figure 11. Tendency of surface air temperature of northern hemisphere (as expressed by slopes of best-fit trend lines) in fifteen year periods 1940-54 and 1950-64. Temperature tendency clearly reversed between these periods over much of the land area of the hemisphere 38.

During the 1970s a succession of great extremes in temperature or precipitation has created the impression that climatic variability is increasing. Extra weight was given to this impression by the relative stability of climate in several previous decades. Some authorities suggest that temperature variability is likely to be increased during periods of cool global conditions or of global cooling. The argument depends on the observed fact that cooling, when it occurs, tends to be greatest near the poles. This increases the pole-to-tropics temperature gradients, and hence the vigour of the atmospheric and oceanic circulations - which then become more prone to large and long-lasting disturbances. The latter create the anomalies of temperature and precipitation.

There have recently been some empirical tests of this hypothesis. Figure 12 shows, for example, the time trend since 1959 of the spatial and temporal standard deviations of air temperature in three latitude belts, and at three levels 39, 61. On balance the evidence supports the view that the spatial and temporal variability of temperature have recently increased, as has the poleward temperature gradient. The period 1973-76 was especially variable in the northern hemisphere. As Figure 12 shows, however, the major effect has been the striking increase in tropical temperature time-variability, especially at the surface, an increase that began following the eruption of Mt. Agung in Bali in 1963. There has also been a progressive increase since 1970 in the area of the northern hemisphere circumpolar vortex of westerly winds, which is consistent with the argument in the previous paragraph. A simple count at individual long-term stations around the globe has shown that low temperature extremes have increased markedly over the past three decades.

However, these results were not confirmed in a recent analysis of the time-variation of temperature, pressure and precipitation over extratropical parts of the northern hemisphere 40. No evidence was found of any recent change in variability in any of these elements. Another forthcoming study 41 will show, furthermore, that the variability of temperatures appears not to increase as mean temperature decreases; in the United States and Europe variability and the mean temperature appear uncorrelated. The evidence for a recent increase in climatic variability outside the tropics is hence equivocal.

6.4 Precipitation since the seventeenth century

Unfortunately we cannot match even this incomplete account of temperature variability with anything comparable for the other central climatic element, precipitation. Rainfall is measured in a very crude fashion by means of small cans whose exposure is often dubious. Snowfall is even harder to measure, since any attempt to catch it tends to create abnormal drifting. Over the oceans both are effectively unmeasurable, and estimates have to be based on the frequency of ship observations of rain or snow, or on satellite cloud observations. Long time series of precipitation are thus hard to come by. Those that we have fail to indicate any major world changes since the seventeenth century.

One such record (Figure 13) comes from England and Wales, where several workers have collected and recalibrated numerous old observations 42. No striking trend is visible, nor do the more pronounced peaks suggest any real periodicities. Some slight decrease in winter precipitation appears to have occurred between 1925

and 1975, but variability continued high. Most of the other long-term records from both hemispheres show similar small effects, but no clear trends emerge on a hemisphere or global basis. A record from Toronto, Canada (Figure 14) does, however, show two effects often visible at other stations: a single, abrupt decrease of mean precipitation of about 10 per cent in the 1860s and early 1870s, and a decade-long drought phase in the 1920s and 1930s (widespread in the northern hemisphere) ^[43]. A long record of Indian monsoon rainfall ^[62] shows no striking changes over more than a century, and fails to indicate either a trend, or a tendency towards prolonged drought episodes (Figure 15). It is possible, however, that the actual area of inadequate rainfall has increased in the past two decades.

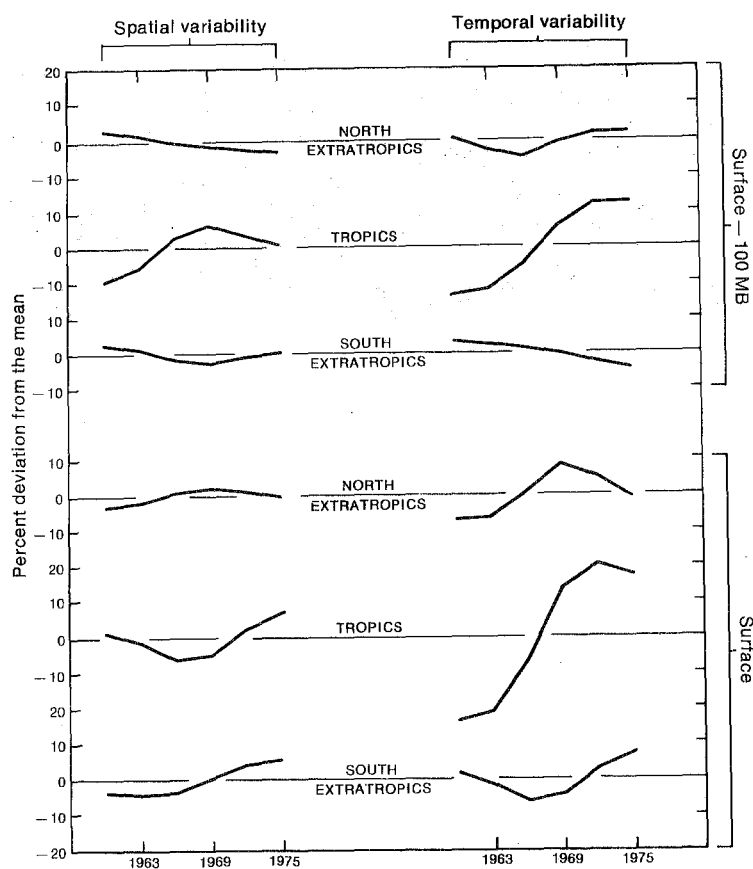


Figure 12. Variation of standard deviation of temperature over the Earth with respect to space (left hand curves) and time (right hand curves), since 1961. Upper curves are for atmosphere up to 100 mb (about 16 km), and lower curves for surface air temperature ^[39].

Although the instrumental record is unsatisfactory there is abundant evidence of the great variability of precipitation, and of its impact on crops and pastoralism. The special effects along the desert margin will be dealt with later. Here we shall confine ourselves to recent events outside the tropics.

Aridity is the name given to permanent inadequacy of precipitation. Aridity is widespread in the world, and must always have been so. Indeed the most ancient sedimentary rocks include certain types that speak of arid conditions. Aridity itself can be readily encompassed by human cultures. It is drought, the failure of normal precipitation over months or years, that has been the chief climatic scourge

of mankind. This is still true even in the most advanced countries. And few parts of the world are immune.

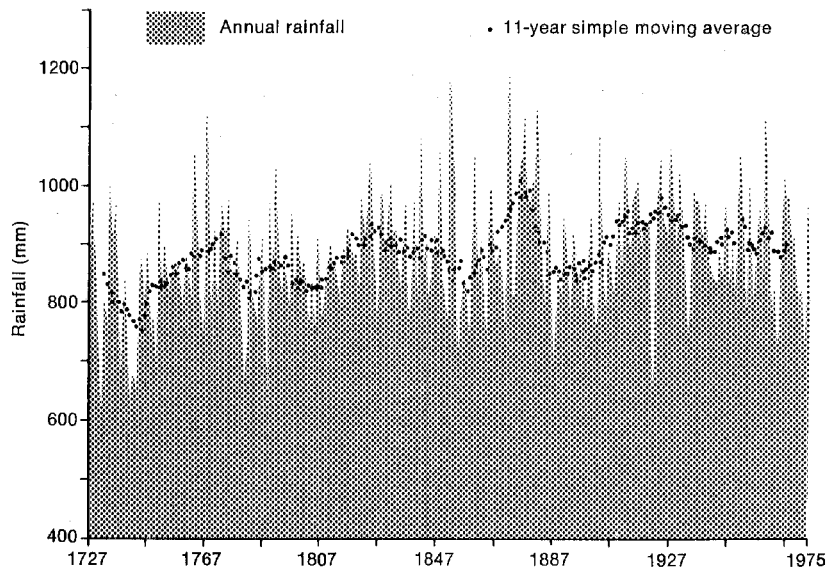


Figure 13. Estimated mean annual precipitation over England and Wales since 1727 42.

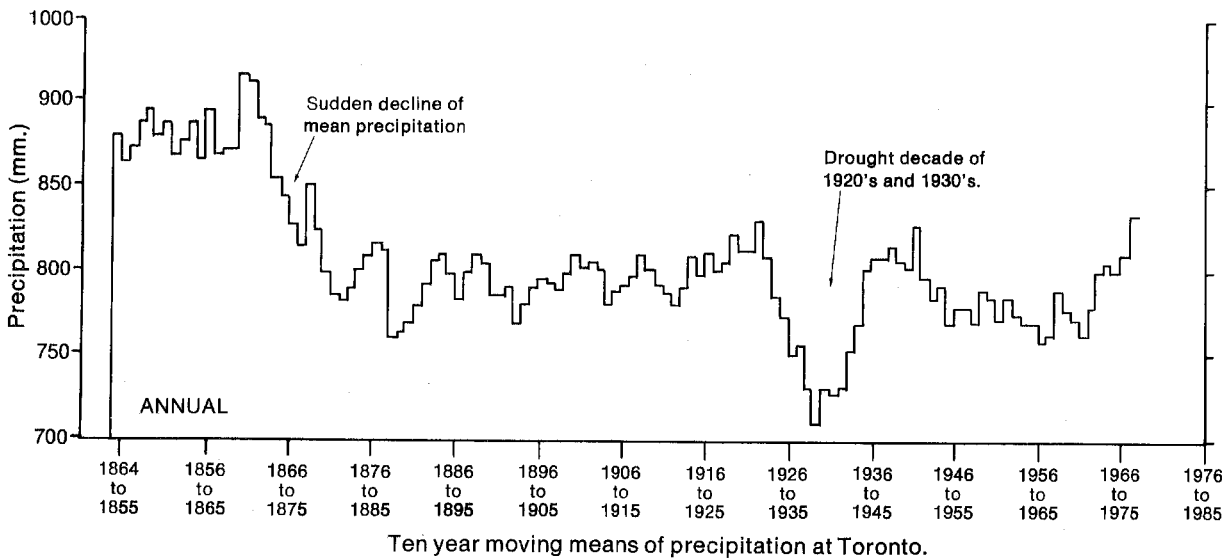


Figure 14. Variation of mean annual precipitation at Toronto, Canada, since 1864, by ten-year moving means, showing apparent decline in late nineteenth century and a decade of drought in the 1920s and 1930s 43.

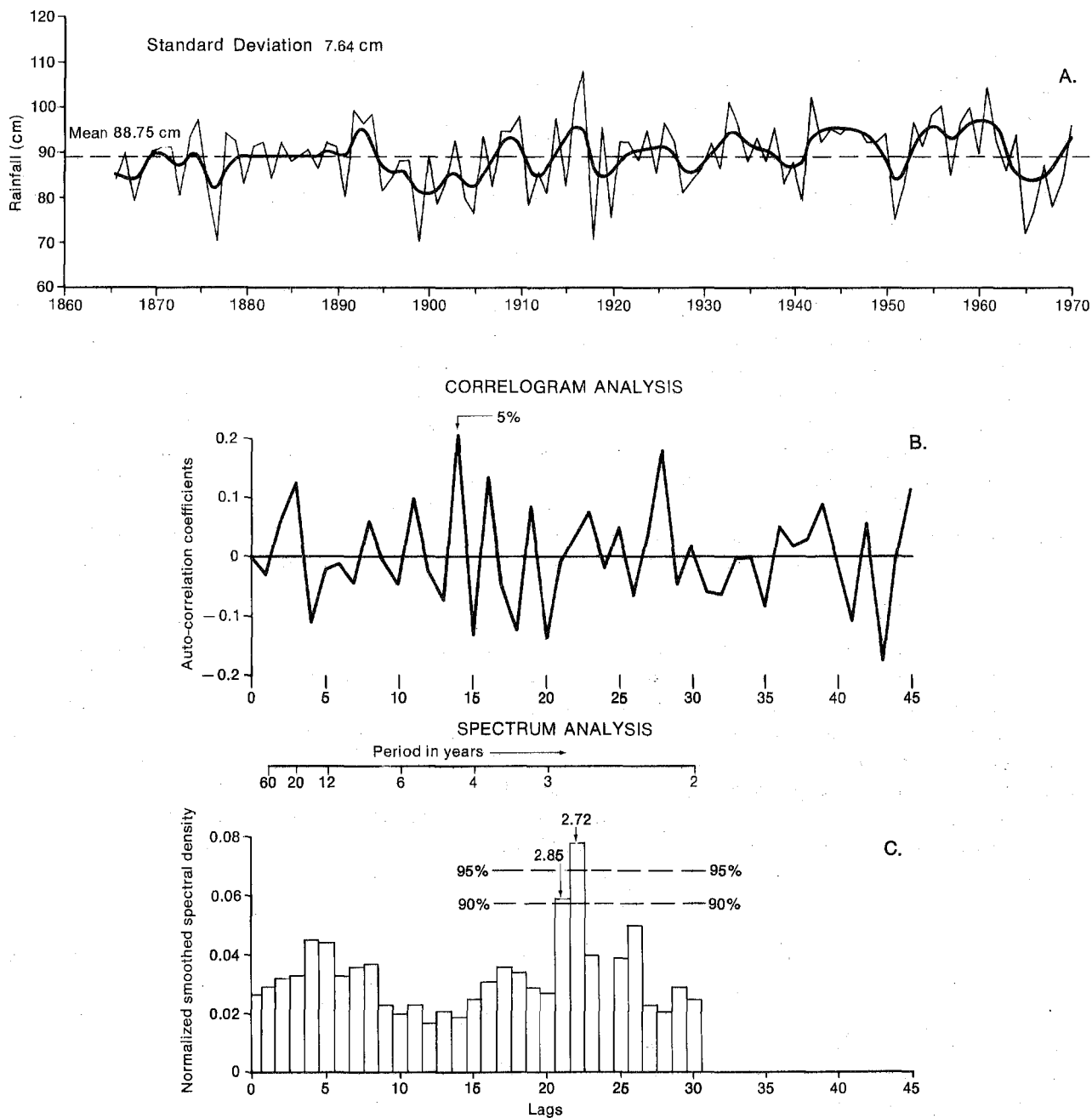


Figure 15. A long time-series of mean annual rainfall (curve A) over India since 1866. The record reveals no significant periodicity except for the 2-3 year period (the quasi-biennial oscillation), and no obvious trend (curves B, C). The period 1931-60 was significantly wetter than the rest of the record 62.

Drought, as so defined, is especially common where rainfall is normally low, as in the arid and semi-arid climates; but it may occur anywhere. The most important droughts in an economic sense are those that affect key agricultural areas. The droughts of the 1930s and 1950s, for example, in the U.S. wheat growing areas had major impacts. So did the repeated droughts in arid, pastoral Australia. These were events affecting food exporting countries. But drought also has a major effect if it hits areas of subsistence agriculture where most food is normally produced locally. The Sahelian drought was of this character and similar droughts have in the past heavily reduced the populations of India and China 44.

During the 1970s drought has been a major contributor to the sudden impact of climate on the human economy. The grain-producing regions of the Soviet Union have several times been badly affected, as have those of China. In North America severe droughts were absent for many years, during which grain production rose spectacularly. But droughts returned in the 1970s, interspersed with excellent years. In Australia the pattern has been one of shifting, severe drought in some regions, while others have had record rainfalls. A drought in 1975-76 in north-west Europe was without local parallel in the past three hundred years. It, too, was short, and ended with excessive rainfall. Drought in northern India was most widespread in 1972, but there has been no return to the high incidence typical of early decades in the century 45.

The inadequacy of records makes impossible a categorical statement about these recent events. Most analyses tend to show that the droughts of the 1970s, although severe, are normal to the climate, in the sense that they have occurred before, and presumably will occur again. Duration, severity and extent have all been matched or exceeded before. What is new is that droughts are hitting a world with a much higher and rising food demand because of rising population. They are also far more visible to others because of improved communications. And there is widespread acceptance of the view that something must be done to soften their impact, whether it be measures to avoid famine or soil destruction, efforts to enhance rainfall artificially or attempts to foresee such events.

Excessive rainfall or snowfall may also have severe economic impacts, including flooding, soil erosion, crop damage and destruction of dams, roads and railways. There is no evidence that such heavy rains have increased in frequency in recent times, but the 1970s have produced some remarkable extremes. After protracted drought culminating in 1972, for example, three successive abnormal rainy seasons in Queensland raised water levels in normally dry Lake Eyre, in central Australia, to shorelines not reached in the past ten thousand years.

Prolonged drought or excessive rainfall arises from abnormalities of atmospheric circulation - essentially the absence or weak performance of precipitation-making disturbances, such as mid-latitude cyclones, or west African disturbance lines. Claims have been made that such abnormalities occur periodically - for example a twenty-year recurrence interval in the U.S. mid-West and Great Plains. But a diligent search of the record fails to sustain this view. An equally diligent search of the record of the Indian summer monsoonal rainfall record 62 also fails to show true periodicity (Figure 15) though a decrease in the frequency of severe drought episodes 44 has been claimed. As far as is known, major drought or wet phases occur without any strict periodicity, though they may have preferred return periods.

6.5 The Sahelian drought

More than any other event, the Sahelian drought of 1968-73 called public attention to the reality of climatic variability and its significance for man. From the early 1960s onwards, the six Sahelian republics suffered a progressive decline in rainfall which culminated between 1968 and 1973 in a drought so severe that it starved flocks and herds, killed an unknown number of pastoralists or cultivators, and damaged soil and natural vegetation, especially woody species. The effect spread at times into Ethiopia, Somalia, Tanzania and Kenya 46. Though rains returned to some areas in 1974 and 1975, drought has persisted in others, and reinvaded West Africa in 1977. The economic and social effects on these African nations have been very drastic. The drought has naturally posed a set of questions. Is the effect a lasting one, or will abundant rainfall return? Should the damaged lands be reoccupied, or should attempts be made permanently to relocate the population and the lands retired from use? Does unwise land-use actually intensify drought, by some species of feedback process? And are there measures to be taken, such as precipitation enhancement, or altered land-use, that may help restore a better climate?

The U.N. Conference on Desertification in 1977 attempted answers to these questions, and substantial climatological research is being undertaken to help in this process.

There is agreement on the following points:

- (a) the drought of 1968-73 was the culmination of a desiccation dating back to the late 1950s or early 1960s in most parts of the Sahel;
- (b) though prolonged, severe and extensive, the drought was not unprecedented (Figure 16). Similar droughts were experienced in the Sahel in the early 1910s, the late 1920s, and in a protracted period in the 1940s 15. No fixed interval seemed to be involved;
- (c) the associated desertification (i.e., spread of non-productive land conditions) was caused by heavy continued stocking or dry land cultivation during the drought years, until the land could no longer sustain the human and animal populations.

Subsequent research has demonstrated that the drought itself was caused by persistent anomalies of the general circulation, but these were not simply due to a southward shift in the sub-tropical high pressure belt 47. Nor was the drought due to lack of water vapour. In fact at the height of the drought, the high-pressure belt was a little further north than usual, and the water vapour available for precipitation was above normal 48. What failed to materialize were the disturbance systems normally responsible for the infrequent rains.

It was also conjectured that the loss of vegetation caused by the desertification might increase surface albedo (reflectivity to solar radiation). Dynamical modelling of the circulation with simulated higher albedos indicated that they should lead to increased subsidence of the air over the area, which should in turn lead to intensified drought - a positive feedback 49, 50. To this extent, and to the extent

that local water supplied to feed shower development is restricted, drought may indeed feed on drought. It has been suggested, in fact, that the desiccation of the sub-tropical semi-arid regions since mid-Holocene times may be a reflection, on an enormous scale, of slow desertification processes of this kind.

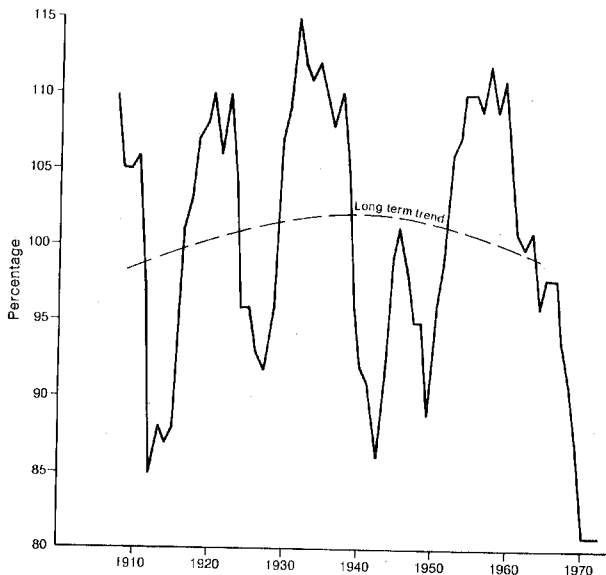


Figure 16.

Variation of mean annual precipitation from group of stations in the Sahel since 1907, with long-term trend 15.

Statistical analysis of the time-series of precipitation over the Sahel shows, in fact, a distinct tendency for drought to prolong itself for several years, well beyond random expectation. This is the phenomenon of persistence, or atmospheric memory, referred to above. Similar persistence affects precipitation anomalies in most parts of the world. The duration of such anomalies may be as economically important as their intensities. The available evidence nevertheless supports the view that the Sahelian drought, though severe and damaging, was an aspect of climatic variability, and not of true variation implying a lasting shift to drier conditions - though there is no sure way of ruling the latter possibility out. As was said in Section 2, the recent impact of climate on the human economy has been largely due to variability, rather than to lasting variation. Even if we were assured that the present climate would endure forever, it would still be necessary to prepare for the kind of stress recently faced by these African nations.

6.6 Forced anomalies

The variability just discussed has been mostly of the spontaneous, internally-generated kind natural to the climatic system - or so we believe. Only at the longer time scales do we have clear evidence that the anomalies may be forced by external agencies. Nevertheless there are certain features of the modern record that are truly forced in this fashion.

The most obvious of these is the significant rise of urban temperatures in the past century, largely due to the release of energy from power consumption and

heat release in residences, vehicles and factories. Such effects are clearly real, and clearly forced. Moreover the emission of heat and of particles from urban areas has been shown to affect precipitation for a short distance downwind. The scale of such climatic forcing, is, however, local or regional, rather than planetary.

More pervasive, and indicative of a potential major disturbance of climatic equilibria, have been the effects of major explosive volcanic eruptions in the past century. The explosive disintegration of Krakatoa in 1883 produced a world-wide cooling, together with spectacular sunsets, as its dust spread round the world and scattered sunlight. The 1963 eruption of Mount Agung in Bali (Indonesia) caused measurable effects 51. Northern hemisphere temperatures from the surface to 16 km fell by about 0.4 deg C beginning about six months after the eruption. Since then they have fluctuated considerably, and a recovery to pre-Agung values cannot be seen in the record. It is controversial whether the drop can really be ascribed to the eruption 39, 52, 61. Only the largest volcanic events can have such effects, but their existence raises speculation that a greatly increased frequency of explosive eruptions could drastically cool the Earth - and may have contributed to the long cooling of late Tertiary times.

One of the most long-lived attempts to prove external forcing of climatic variations has been the search for links with variations in the sun, notably the 11-year cycle in sunspot numbers and other sunspot cycles 53. Increased sunspot activity does not significantly alter the total energy received from the sun, but does lead to changes in ultraviolet and particle emissions. Though no physical mechanism to link such small effects with disturbances of the lower atmosphere has been demonstrated, the search of the climatic record goes on. A great many significant correlations have been established between short climatic time-series and sunspot number, but these often disappear when longer records are inspected; or phase differences appear that make the correlations look accidental. The most recent of these attempts concerns an effect due to solar rotation, i.e., the passage of reversed-magnetic sector boundaries past the Earth. Recent research has suggested that such events have statistically real impacts on atmospheric wind systems 54, 55.

In general, however, the forced anomalies that one can see in the climatic records, apart from daily and seasonal effects, are small by comparison with internally-generated variability. Moreover they are generally non-periodic and unpredictable.

6.7 Teleconnections

The atmosphere does much of its work on large geographical scales, so that climatic anomalies tend to be extensive in space. If one station in central North America or Asia has a cold winter, a very large area around it is likely to be similarly affected. The Sahelian drought was longitudinally Africa-wide. Hence climatic distributions typically show considerable consistency over wide areas. The chief exceptions arise from, for example, thunderstorm-type rainfall, which is usually patchy.

On even larger scales, it is common to find the variation of some element in one area correlated with its variation in another area, sometimes quite remote;

or correlations may exist between different elements over such distances. These teleconnections, as they are called, are of great interest, because they must be caused by some process that might otherwise escape attention. Moreover, some of the observed teleconnections have time-lags, meaning that a change of some element in one area typically precedes a correlated change in another 56.

Such effects are actually predicted by the general circulation models developed for the atmosphere. Figure 17, for example, shows a model prediction of the effect on precipitation of a large increase of surface albedo over the Sahara and the dry western regions of North America 57. The model predicts considerable decreases of precipitation over and near the regions of albedo change. But it also predicts changes over other, quite remote areas - teleconnections, in fact. Some of these are increases in precipitation. The general principle involved is quite vital - that changes induced in any one area of the world are likely to produce other changes elsewhere, on a world-wide basis. Thus attempts to modify climate are of concern to the entire world community.

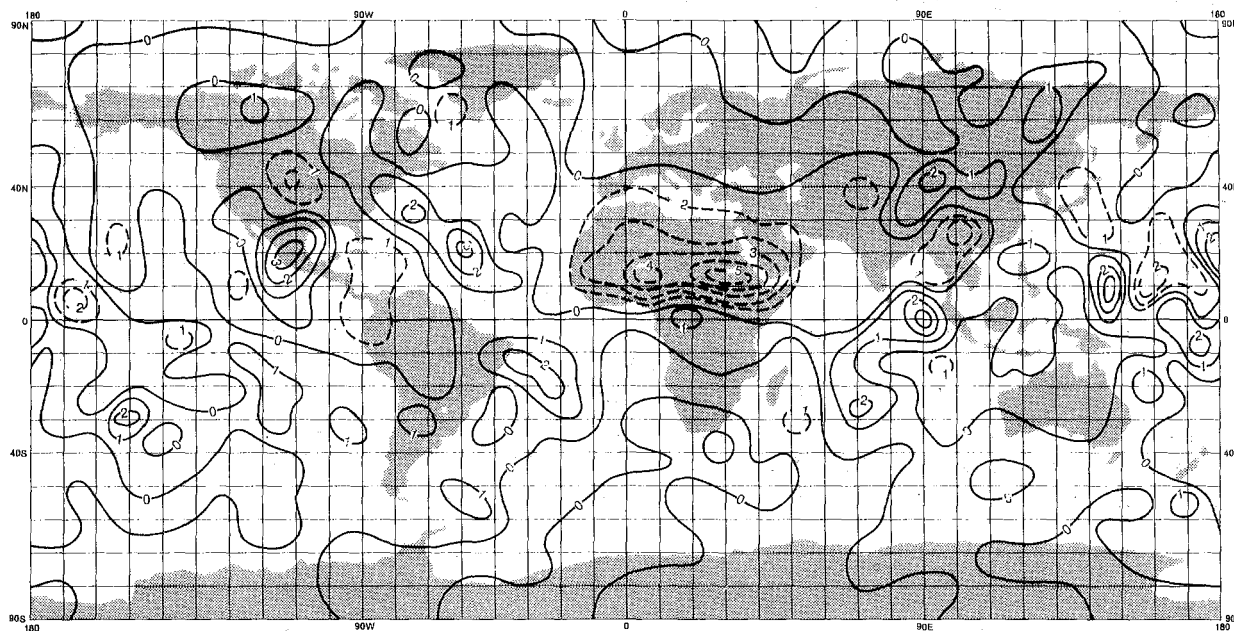


Figure 17. A general circulation model calculation showing expected effect on mean rainfall rates (mm d^{-1}) of an increase of albedo to 45 per cent over North Africa and western North America. Negative isopleths are dashed. The calculation (for July) shows many deviations of either sign in areas remote from imposed perturbations, i.e., teleconnections. Some of these are statistically significant 57.

Many examples of such teleconnections have been demonstrated. The most remarkable is the so-called Southern Oscillation of the Pacific and Indian Oceans, first demonstrated over fifty years ago by Sir Gilbert Walker. It has been defined as ... "a fluctuation in the intensity of the intertropical general atmospheric and hydrospheric circulation over the Indo-Pacific region, the fluctuation being dominated

by an exchange of air between the southeast Pacific subtropical high and the Indonesian equatorial low" 58. It can be measured by means of the simple pressure difference between Easter Island in the southeast Pacific, and Darwin in tropical Australia. Pressure at these two places is negatively correlated, the difference between them varying from small values to as much as 20 mb. More elaborate indices exist, but confirm the reality of the effect. The Oscillation varies in period from 3 to 7 years. In effect it is an immense standing east-west oscillating system, involving large shifts of masses of air and water.

The Oscillation has been shown to influence precipitation over India, tropical Australia and Indonesia, and to be correlated also with rainfall variations in the remarkable equatorial dry belt of the eastern Pacific, which extends from Ecuador to Nauru, in 170°W 59. The most dramatic of these effects is El Niño, the remarkable marine anomaly that recurs every few years off the west coast of equatorial South America. Normally (see Figure 18) cold upwelling water occupies these areas, which are prolific in marine life and the scene of rich fisheries, notably for anchovy. But about a year after each peak of the Southern Oscillation (with strong trade winds over the equatorial central Pacific) there is a tendency for warm water to invade the area - El Niño, as it is called - with dramatic reductions in fish yield. The 1972-73 El Niño, in particular, preceded the collapse of the anchovy fishery, with drastic effects on world agricultural markets, because of its relation to fishmeal (see overview paper by Cushing).

Other teleconnections are known from the tropical Atlantic, for example between sea-temperatures in the Guinea sector off Africa and rainfall in the dry belt of north-east Brazil. Indeed there are clear links between the Atlantic and Pacific atmospheric circulations.

Within the higher latitude westerly belts, teleconnections are also numerous. One well-known effect is a see-saw of pressure and temperature between the Greenland and Norwegian sectors 60. Here again a correlation can be demonstrated between Atlantic and Pacific sectors.

Though real, few of these teleconnections have significant predictive capabilities because they are overridden by other effects, and do not explain much of the total variability. Their main importance is the challenge they throw down to the theorist. For they say something about the characteristic time and space scales of atmospheric behaviour, in many cases well ahead of our capacity to explain them. Effective models of the general circulation must be capable of predicting the existence of such teleconnections.

7. Conclusion

No simple conclusion emerges from this review of climatic variation and variability over the ages - not even from the most recent epochs, when abundant information is available. Climate is a topic that lends itself to facile generalization and to warnings of impending disaster. Such liberties are perhaps best avoided.

A first impression that one gains is of underlying stability. Though the endless variability of climate on all time-scales has been well proven, so also has

the atmosphere's ability to return to a state not very different from its long-term condition. This stability rests on a wide range of mechanisms, most of which are negative feedback loops. Thus the present buildup of carbon dioxide in the atmosphere offers an opportunity to the biota to increase its productivity - and hence ultimately to increase the store of carbon in organic materials, at the expense of the atmosphere. And there is much evidence that the source of nearly all climatic energy, the sun, is quite conservative in behaviour 53, 87.

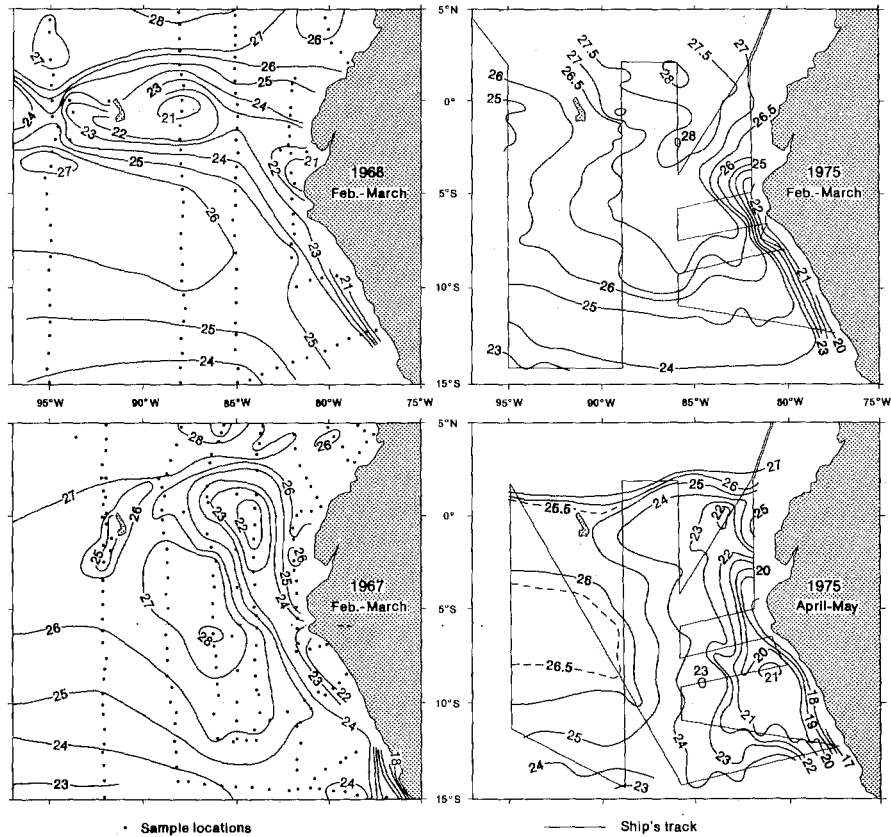


Figure 18. Sea-surface temperatures over Pacific west of South America in four periods, to show occasional intrusion of warm equatorial water into areas normally dominated by cold upwelling (El Niño phenomenon) 587.

But the fact of endless variability about this stable condition remains, mainly reflecting the internal instabilities of the system. This variability would be even greater if the non-atmospheric parts of the climatic system did not exist. In general they act to stabilize the atmosphere. Nevertheless the latter retains much freedom to vary. And there have been external forcing mechanisms at work to add to the variability. Such huge processes as the drift of continents, still in progress, and the raising of mountains by Earth movements, have clearly acted in this fashion. So has modern man, who is changing the composition of the atmosphere at a remarkable rate.

This Conference is concerned with the impact of climate on human affairs. Obviously the main impacts have been due to internal climatic variability rather than to profound climatic change. During the past 1 000 years mean annual surface air temperatures over the Earth have probably varied by less than 1.5 deg C. This is enough to have had some impact, especially on mid-latitude farming. And in high latitudes, where such variations are usually larger, the impacts have been severe. Overwhelmingly, however, the main economic stress of the past decade has been due to short-term climatic anomalies of precipitation - drought in Africa, Eurasia and Australia; floods in Bangladesh, Pakistan and the United States. The economic apparatus constructed by modern man seems still vulnerable to such variability.

Much might be done to protect the economies of nations against such anomalies. The first step required is that decision-makers should develop a better and longer memory for climatic stress and be prepared to deal with it. A year or two after drought has ended, or floods have subsided, many countries lose interest in measures to prepare for the next extreme - which will certainly come. The second step is that atmospheric scientists should make sure that they, too, are fully aware of climatic variability in all its guises, and be prepared to fight hard for its recognition by decision makers. A third step, is to understand the causes of variability, and from that understanding to extract the great prize of successful prediction. And a fourth - still elusive, and perhaps hardly attainable - will be the deliberate attempt to prevent undesirable anomalies, by means of climatic control.

The main aspects of climatic variability that need to be so recognized are these:

- (a) the direct impact of climate on human affairs arises from its variability, on short-time scales for the most part, but also on long-term variation;
- (b) the high variability of temperature and precipitation during the 1970s may not, in fact, have been abnormal; but the major anomalies have hit key areas, such as cereal growing regions or major pastoral belts. It is reasonable to expect that such harmful anomalies will continue. Since the main effects are non-periodic, exposure of a region to stress does not confer immunity against a renewal, even in the shortest term. Thus severe drought returned to the Sahel after only two or three years of good rains;
- (c) the recent trend of atmospheric and sea-surface temperatures has been downward, at a rate of 0.1 to 0.2 deg C per decade, at least in the northern hemisphere. It is not clear whether this will continue. It may be offset by heating due to atmospheric contaminants such as added carbon dioxide, or chemical synthetics (discussed by other overview authors). The general trend of planetary temperature has been downward for 50 million years. The present decline, however, is probably part of a shorter-term fluctuation typical of records of the more recent past;

- (d) variability of surface temperatures is highest in middle and high latitudes. Northern countries will be more affected than those of tropical, sub-tropical and warm temperature zones. Production of spring wheat, hay and dairy produce may be vulnerable to temperature variability. So also may be power demands;
- (e) variability of precipitation is widespread, and affects all countries. But its worst effects lie in sub-humid or semi-arid areas, such as the former grassland areas of temperate zones and the margins of the sub-tropical or warm temperate deserts. Regions dependent on a single rainfall source, such as monsoonal currents, are especially vulnerable. The absence of prolonged droughts from monsoon Asia in recent decades may not continue. There is no sign that the high frequency and great extent of recent African droughts are about to end;
- (f) the best defences against climatic anomalies are in all cases to adopt economic practices that take account of their probable return. An enemy of world food production has been our short memory for climatic extremes. In time we may learn to predict or conceivably control some of these anomalies. It is vital that we try to do so, with more resources than in the past. Meanwhile, only cautious farming methods, a further search for tolerant crop varieties, control of dry-land pastoralism, better design of water supply and power systems, and similar measures can be advocated.

But these technical devices need to be coupled with the realization outside the scientific world that climatic variability is one of the key influences on human economic performance. That is the lesson that the events of the past few years should convey. It is one of the messages that should emerge from this Conference.

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CLIMATES OF PAST GEOLOGICAL EPOCHS

I. P. Gerasimov*

The science of the climates of past geological epochs, i.e. paleoclimatology, has become of very considerable current importance. One of the reasons for this is the growing concern of the world public as to the possibility of great changes in contemporary climate, and as to the influence of such changes upon the natural environment. Present-day paleoclimatology is being confronted with the task of reconstruction, on the basis of paleogeographic data, of past climates and natural trends of long-term climatic changes that can be treated as analogues of the most probable climatic conditions of the future. This allows an additional substantiation of climatic forecasts put forward on other grounds and provides data against which mathematical models can be checked.

However, the task of creation of authentic reconstructions of climates of the past is not easy. First, these reconstructions are based on information much more limited than the information used for the study of contemporary climates. Second, they are based on the application of a methodology which yields results that are largely of a probabilistic character.

The main information on climates of past epochs is extracted from ecological interpretation of paleobiological materials, that is of macro- and micro-remains of plants (pollen and spores included) and of animals (bones and testaceous remains) buried in geological deposits of different ages on continents, and in the sediments on the bottom of seas and oceans. This basic information is supplemented by the study of generic types of ancient fossil soils, of weathering crusts, and of lithoclimatic facies of laterite deposits (for instance of cabooks, kaolins, bauxites, loesses, and others) and of lake and marine sediments. Essential paleogeographic (including paleoclimatic) information is being accumulated also from historical and archaeological materials.

Recently there has begun a wider and rapidly growing use of geochemical methods (mostly with isotopes) in paleoclimatic investigations. Among these the most important are absolute age datings, paleotemperature measurements in the remains of microfauna, shells of fresh-water and sea molluscs, osseous remains, samples of ancient ice, and so forth. The volume of information obtained in this way is growing fast, although such information still remains insufficient.

For certain paleogeographical situations it is also possible to use, with a view to paleoclimatic reconstructions, models of the general theory of climate. On the basis of introducing in such models the corresponding limiting parameters it is

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theoretically possible to reconstruct the meteorological régimes of geological epochs of the past.

In the sphere of investigations of climates of the past it is expedient to distinguish at least three main temporal ranges of investigation: recent climatology, historical climatology, and climatology of past geological epochs (or paleoclimatology). Besides differences in time intervals, in every one of these three ranges of investigation distinct original data are used. Recent climatology deals with results of direct meteorological observations and covers the period of the last hundred years of our times. Historical climatology is based on reports of ancient chronicles which noted one or another meteorological phenomenon, as well as on those natural objects which contain exact chronological data (such as, for instance, tree rings or dendrochronology). This range of investigation already covers several thousands of years. And last, paleoclimatology operates, as was indicated, with diverse paleogeographical data, mostly paleobiological and geological data. This range covers many million years of geological history.

Traditional paleoclimatic reconstructions are based on a principle of "actualism". This principle, in its turn, is based on the assumption that ancient species of plants and animals used as paleogeographical indicators needed the same climatic conditions in the past geological epochs as related species of the organisms do at the present time. The same also refers to ecosystems (biocenoses) as well as to weathering crusts, to soils, to lithoclimatic facies of continental deposits, and so forth. This approach permits the description of paleoclimatic characteristics in quantitative terms.

Thus, for example, as illustrated in Table 1, geographical zonality is related to indices of the thermal energy base (radiation balance of the Earth's surface) and of conditions of moisture (the radiational index of aridity) for all major contemporary macrotypes of natural ecosystems. Taking this dependency into consideration, it is possible to determine values of radiation balance and of radiation index of aridity on the basis of data on geographical zones in the past, i.e., the values corresponding to these zones. With sufficient exactitude for paleoclimatic reconstructions, use may be made of the main characteristics of climate (for instance, mean temperature values for winter and for summer, totals of annual atmospheric precipitation) peculiar to conditions of formation of present-time weathering crusts, soils and of lithogenetic facies of continental deposits (Table 2). Definite climatic indices characterize optimum conditions for existence of individual species of plants and animals, and of their communities, groups, and complexes. In recent years it has also been possible to determine the temperature conditions for the existence of contemporary plankton complexes of the world ocean.

All this creates naturally a foundation wide enough for paleoclimatic reconstructions. The significance of such indices, however, especially of paleobiological indices, is sometimes a cause for doubt from the point of view of evolution, since modern plants and animals in many instances are of a rather recent geological age. Their predecessors, that is, more ancient species already extinct, could have had both analogous and differing climatic requirements. It is true, nevertheless, that there exists the possibility, by way of studying morphological peculiarities of organisms that have disappeared, of comparing them with those species existing at the present

Table 1

Table of geographical zonality (after M. I. Budyko, 1977)

Thermal energetic base - radiation balance	Conditions of moisture - radiation index of aridity								
	Less than 0 (extreme surplus moisture)	Surplus moisture				Optimum moisture 4/5-1	From 1 to 2 (moderate insufficient moisture)	From 2 to 3 (insufficient moisture)	More than 3 (extremely insufficient moisture)
		0-1/5	1/5-2/5	2/5-3/5	3/5-4/5				
Less than 0 (high latitudes)	I Permanent snow	-	-	-	-	-	-	-	-
From 0 to 50 kcal cm ² per annum (south Arctic, sub-Arctic and middle latitudes)	-	IIa Arctic desert	IIb Tundra (with sparse wood islands on the south) flooded scrubs	IIc Northern and middle l taiga	IIId Southern taiga and mixed wood	IIe Leaf-bearing wood and wooded steppe	III Steppe	IV Moderate belt semi-desert	V Moderate belt desert
From 50 to 75 kcal cm ² per annum (sub-tropical latitudes)	-	-	IVa Regions of subtropic hemigelia with large amount of swamps	VIb Pluvial subtropical forests		VII Hard-leaf subtropic wood and shrubs, fall-leaf wood	VIII Subtropical semidesert	IX Subtropical desert	
More than 75 kcal cm ² per annum (tropical latitudes)	-	-	Xa Regions with prevalence of equatorial wood swamps	Xb Very over-wetted (plenty of swamps) equatorial wood	Xc Middle over-wetted (average swamp) equatorial wood	Xd Equatorial wood merging into light tropical wood and wooded savanna	XI Arid savanna woods with falling leaves	XII Desertified savanna (tropical semi-desert)	XIII Tropical desert

Table 2

Climatic characteristics of contemporary natural formations

	Main types	Climate	Temperatures		Atmospheric precipitation (cm per annum)
			Winter	Summer	
Weathering crusts and continental deposits	Siallite	cold	-10° and below	+10° and below	250
	Gleyey	moderate-humid	below	below	
	Siallite	moderate-cold; moderate-humid	0° and below	10-20°	250-500
	Siallite (carbonate, loesses, etc.)	warm; dry	0-10°	20-30°	100-250
	Ferralitic (laterite crusts, etc.)	hot; variable-dry	10-20° and above	30° and above	500
	Allitic (kaolines, bauxites, etc.)	hot	10-20° above	30° and above	500
	Tundra gleyey	cold; moderate-humid	-20° and below	+10° and below	250
	Taiga podzol	moderate-cold; moderate-humid	-10° and below	10-20°	500
	Steppe (chernozems, etc.)	warm; moderate-dry	0-10°	20-30°	500
	Desert (sierozems, etc.)	warm; dry	0°	30-40°	250
S i o l s	Subtropical (red earths, etc.)	warm moderate-humid	0-10°	30-40°	1 000
	Tropical dry (red earths, etc.)	hot; dry	10-20°	30-40°	1 000
	Tropic humid (lateritic, etc.)	hot; humid	20°	30-40°	1 000
	Loess, brown grey	warm; moderate-humid	0-10°	20-30°	1 000
Cryogenic formations	Permafrost	cold moderate-humid	0-10°	20-30°	1 000
	Contemporary glaciation covers	cold; dry	-30° and below	0°	250

NOTE: Climatic indices are calculated from data on the maps of the Physico-geographical Atlas of the World (Moscow, 1964)

time, and on this basis to derive some other paleo-ecological conclusions (for example, thermophilic features, xeromorphism, and so forth) although such conclusions are also of a probabilistic character.

At first glance, it may seem that the application of the latest geochemical methods provides for more assured quantitative paleoclimatic information. It is known, however, that such information is usually constructed on the basis of definite hypotheses, at the root of which lie regularities of contemporary natural phenomena. Thus, for example, data on paleotemperatures based on the correlation between temperature and the relative amounts of the isotopes of oxygen, ^{16}O and ^{18}O , result from the assumption that the chemical composition of ocean waters in the past did not differ from that of the present. The same can also be said of radio-carbon dating, although some historical and geological corrections are being introduced into it. Thus the latest methods of obtaining paleoclimatic indices, to a certain extent, also depend on the principle of actualism.

As shown already, with accumulated experience in paleogeographical reconstructions their exactitude is increased if one gets similar results with the help of independent methods: paleolithological, paleopalaeontological, paleobiological and others, supplemented by geochemical (isotope determination) and geophysical (physical modelling on the basis of application of the theory of climate) methods.

Alongside this, the point should be emphasized that, because of rather poor paleogeographical information for the more ancient geological epochs, and also due to the growing limitations in the use of principles of actualism and in the applications of models of the theory of climate, the general degree of scientific substantiation and detailed character of paleoclimatic reconstructions decreases as one goes back in time. The growing difference between climates of more ancient geological epochs and those of the present time also supports this point of view. When going back to more ancient epochs, the forecasting role of paleoclimatic investigations also diminishes.

Paleogeographic investigations conducted with the help of various methods have made possible a number of important paleoclimatic generalizations. Important among them was the idea of the prevalence on the surface of the Earth during all the Mesozoic Era (before the Pliocene) of hot climates, with weak seasonal changes, and of a concentric distribution of zones of land with various levels of moisture. At the same time specialists admitted the existence of a general tendency towards cooling - during the Meso-Cenozoic era - of the climates of temperate and high latitudes, with an increase in the contrasts between seasons as well as a gradual complication of the climatic zonality leading to a growing diversity of the Earth's climates. This process has been further complicated by cyclic fluctuations of climatic conditions with different amplitudes.

Such is the general scheme of paleoclimatic conditions of the Meso-Cenozoic eras drawn from a number of well known works [1, 2, 3, 4, 5, 6, 7]. It should be noted that a concrete definition of the above general scheme of paleoclimates of the Meso-Cenozoic eras described in these works, as well as in many others, is given in essentially different ways. This can be explained by many difficulties in interpretation of paleogeographical information, and by the need to use different theoretical reconstructions and historico-geological models for the generalization of the empirical

evidence. Of special importance is the fact that in many investigations of climates of the past, a model of constant distribution of the land areas and of oceans is laid into the foundation of paleogeographical reconstructions /3, 5, 6/. This is not the case, however, with the work of W. Köppen and A. Wegener /2/, in which for the first time a theory of drifting continents (and also of migrating poles) was proposed.

It is common knowledge that at present the theory of continental drift (and of polar migration), and the so-called theory of plate tectonics, are more widely used for explaining many phenomena of geological history. According to these theories, back at the beginning of the Mesozoic period there existed a sole continental land mass (Pangaea) surrounded by the world ocean. During the Meso-Cenozoic eras the mass of Pangaea became dismembered, and there appeared a number of continental blocks which drifted apart, and which formed the present-day continents. The use of this historico-geological model for explanation and concrete definition of the general scheme of climates during the Meso-Cenozoic era is an urgent task for paleoclimatic reconstructions. Scientific developments of this kind can be found in the materials and proceedings of international conferences devoted to problems of paleoclimatology, some of which have taken place recently (Newcastle, 1963; Norwich, 1975, etc.). It is also found in works by individual scientists, for example in the latest investigations by Lamb /8/, by Flohn /9/ and others.

Budyko offered some theoretical substantiations /10, 11/, which proved to be most interesting for paleoclimatic investigations of this kind. He recognized the energy balance between the atmosphere and the hydrosphere as the most important factor in the formation of land climate in the geological past, with heat transfer between the poles and the equator effected by ocean currents also playing a significant role. Since, in conformity with the above historico-geological model, during a large part of the Meso-Cenozoic era there existed a vast world ocean, or in any case there was free ocean circulation between polar and equatorial latitudes, meridional heat transfers should have played a greater role as compared with the present epoch. This factor explains very well the prevalence of hot climates during these geological epochs as well as the development, primarily on the continents, of concentric climatic belts with different levels of moisture.

Different phenomena might cause cyclic changes of climates and differences in the amplitudes of these cycles in the Meso-Cenozoic era. In this regard the most important is believed to be a change of the gas composition of the atmosphere and, in particular, fluctuation in the CO₂ content. Among many such studies I again draw attention to the works of the Soviet scholar M.I. Budyko, who used historico-geological data for compiling the well known curve of the geological evolution of the atmosphere's gaseous composition for 200 000 000 years, i.e., for the Meso-Cenozoic era (Figure 1). According to this curve, along with a general tendency towards a decrease of the CO₂ content during the Meso-Cenozoic era there were repeated cycles of its increasing and decreasing. Leaving aside the reasons for this global phenomenon (M. I. Budyko mainly explains it by cyclic volcanic activity), we should keep in mind that in the majority of recent studies the periods of an increased content of CO₂ in the Earth's atmosphere are associated with the so-called "greenhouse effect" in the change of the structure of the atmosphere's radiational balance and, consequently, an epoch of a considerably abnormal rise in temperature. (See papers by Munn and Machta, Flohn and Mason.) As a result of all this some sensational paleoclimatic concepts have come into being.

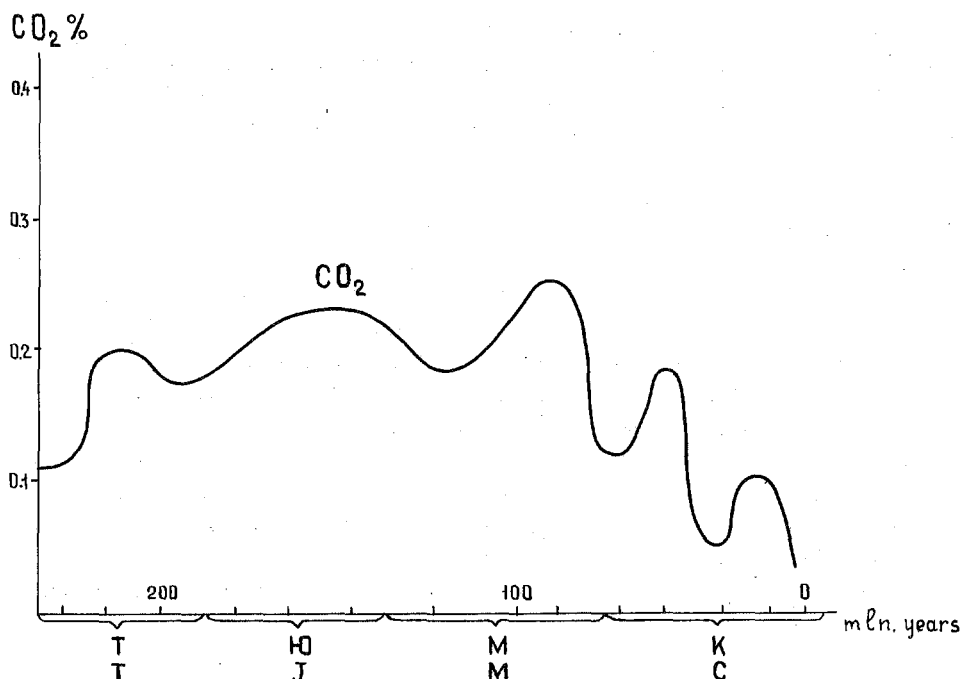


Figure 1. Evolution of the gas composition of the atmosphere (after M.I. Budyko, 1976)

The article by McLean ^[12], can serve as a vivid and concrete example of such works. In the article the author considers the so called "Time of Great Extinction" - the disappearance in large numbers from the Earth of many representatives of the Mesozoic period fauna living at the end of that period and on the boundary with the Cenozoic period that followed. Using data of the latest investigations conducted by many scientists, the author of the above article proves with conviction that a sudden and rapid warming of the general climate caused by a sharp increase in CO₂ concentration in the atmosphere, together with its "greenhouse effect", was the main reason for that global biological catastrophe (ecological crisis). Dwelling on investigations which prove the present increasing anthropogenic CO₂ concentration in the atmosphere, he predicts a new ecological catastrophe for life on the Earth similar to that of the Meso-Cenozoic one.

In my report there is no possibility to discuss the many ecological catastrophes of the Meso-Cenozoic period. It goes without saying that geological history has been characterised by paleogeographical changes on a catastrophic scale. It is sufficient to recall that during the beginning of the disintegration of the unique land mass (Pangaea), there was a development of oceanic spreading and subduction, as well as the beginning of the Laramy-Alpine orogenesis, formation of the Tetis and so on. Moreover, the curve by Budyko (Figure 1) is valid for the evolution of the atmospheric composition in the geological past, and it is surprisingly similar to the report by Bolin presented at this Conference, predicting an anthropogenic effect because of burning of fossil fuels. These pieces of evidence all point to the earlier

as well as to the future high "wave" in atmospheric CO₂ concentration, and indicate a possible manifestation of a strong "greenhouse" effect.

However, in our opinion, it is not valid to make a simple analogy between the geological past and the future, and to identify the Meso-Cenozoic epoch "hothouse" with the forthcoming "greenhouse" of anthropogenic origin. Even if we do not touch upon the purely biological aspects of the ecological crisis of the Meso-Cenozoic period, purely paleogeographical arguments contradict such an analogy. Thus, for example, the whole surface of the Earth would have to suffer a swift and radical rearrangement before another similar biological catastrophe could repeat itself. Instead of the richness and diversification of modern nature, with abundant safe ecological niches - shelters from various climatic adversities - our planet Earth should once again transform into a single homogenous land devoid of natural shelters, another Pangaea washed by the vast and also single world ocean. In Figure 2, based on historical and geological reconstructions by Sinitsyn [7], it is shown how for Eurasia, as an example, climates over land in the course of geological evolution have been becoming more complex.

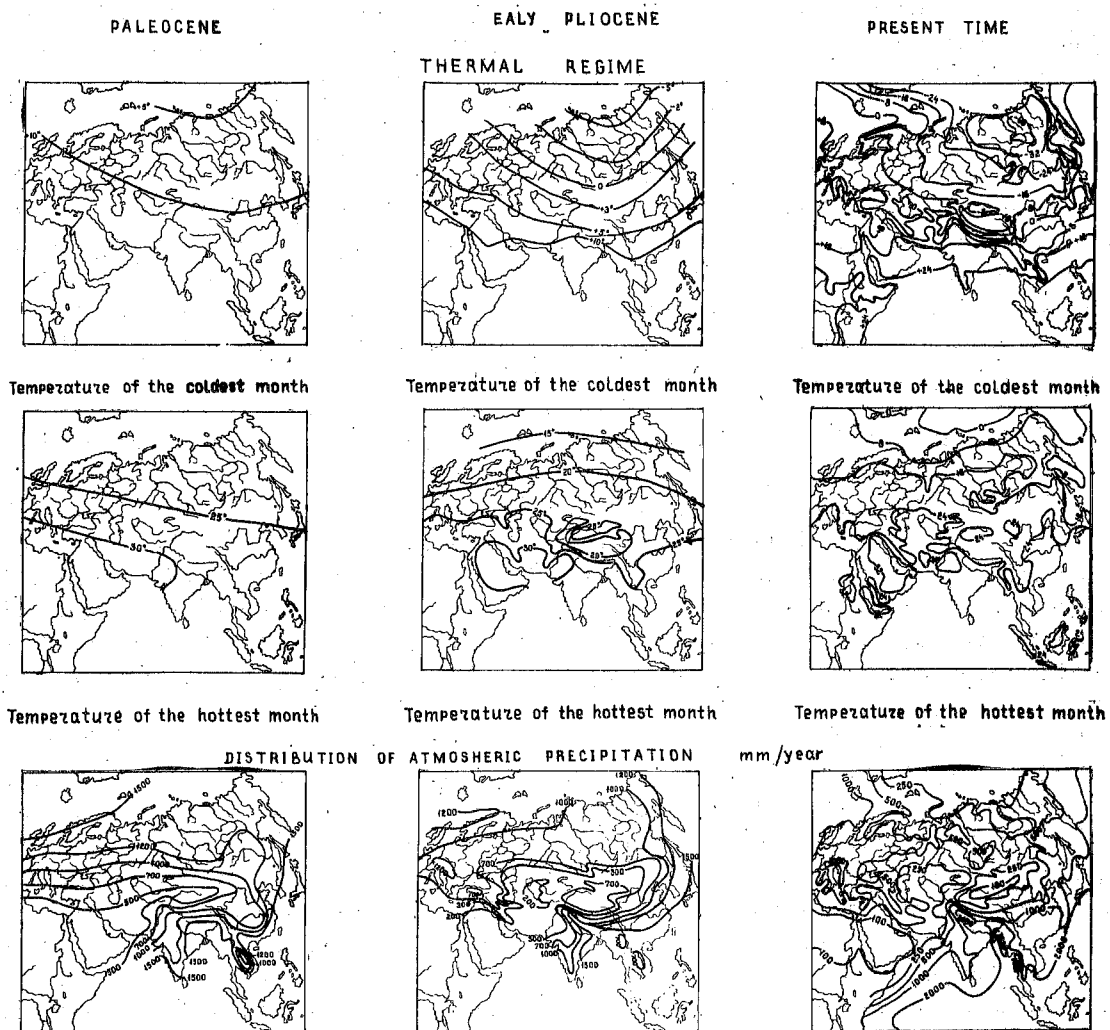


Figure 2. Paleoclimatic reconstructions for Eurasia

Now let us turn our attention to the latest stages of this evolution. As has been stated above, it is common knowledge that during the Cenozoic era a general global cooling was developing, together with an increase in seasonal contrasts and a complication of natural climatic zonality. Such a transition is well documented for the Miocene and Pliocene (Figure 2). Budyko [11] explains the transition by the fact that during the Tertiary isolation of the North Polar basin from tropical regions of the ocean was developing gradually. This caused a drop in temperature near the North Pole, and led to a temperature distribution typical of the glacial epochs of the Quaternary.

It is interesting to note that the process of cooling gradually became evident both on land and in the world ocean, as is clearly proved by the data given in Figure 3.

Data on changes in the climate during the Cenozoic era can be used in making forecasts. In that respect special attention should be drawn to the pre-glacial period, that is, the period in the paleogeographical evolution of the Earth when climate-forming factors favouring the onset of glaciation were not yet prominent, although the geographical disposition of continents and oceans was very close to that of the present time. In the survey by Schwarzbach [6] the climate of that time is characterized in the following way: "On the whole, climate of the Pliocene was very similar to that of modern times, although it was a little bit warmer" (p. 197). In the survey by Brooks [3] it is stated that "climatic zones in Europe during the Mio-Pliocene were displaced by 10° or 15° to the north in comparison with their present location" (p.12). Lastly, in the contemporary monograph by Lamb [8] summarized data are given on paleotemperatures in the southern hemisphere, and it is shown how tropical conditions there have been changed into sub-tropical and temperate ones. Generalization of all data of this kind is sufficiently substantiated to allow for their use in making forecasts of future climates.

In the report to this Conference made by Flohn, the greatest importance is attributed to this geological period for forecast purposes. It is called a period free of ice in the Arctic and with an ice-covered Antarctic continent, its age being determined as from 12 to 2.5 million years ago. Discussion of the hypothetical model of paleogeography of that period which is described in the report by Flohn seems to me as a very interesting subject for our scientific exchange of opinions. According to Flohn's summary, anthropogenic increase of CO_2 concentration, in the author's view, can in the near future lead to "reproduction" of the paleogeography of that particular period.

It seems to me important to note that latest archaeological findings of the most ancient man (more exactly, of a prehistoric man) which were discovered in East Africa (by Leaky) refer to the later part of that particular period of time. The phylogenics of the human race is recognized to be of a rather complex character, covering the last 2-3 million years. The question of the role played by the natural environment in shaping the appearance of ancient man is quite interesting and is still only vaguely understood. The region of rift valleys in East Africa was characterised by a rather diversified forest-savanna landscape. A hypothesis has been put forward that the most important role in the transition from primates to the pre-historic man was played by his omnivorousness, his high mobility, and his ability to actively attack

or defend, such features having freed these primates from their ecological "niches" and having provided for a possibility to live and exist in various natural ecosystems. However, this was just a relative independence from Nature.

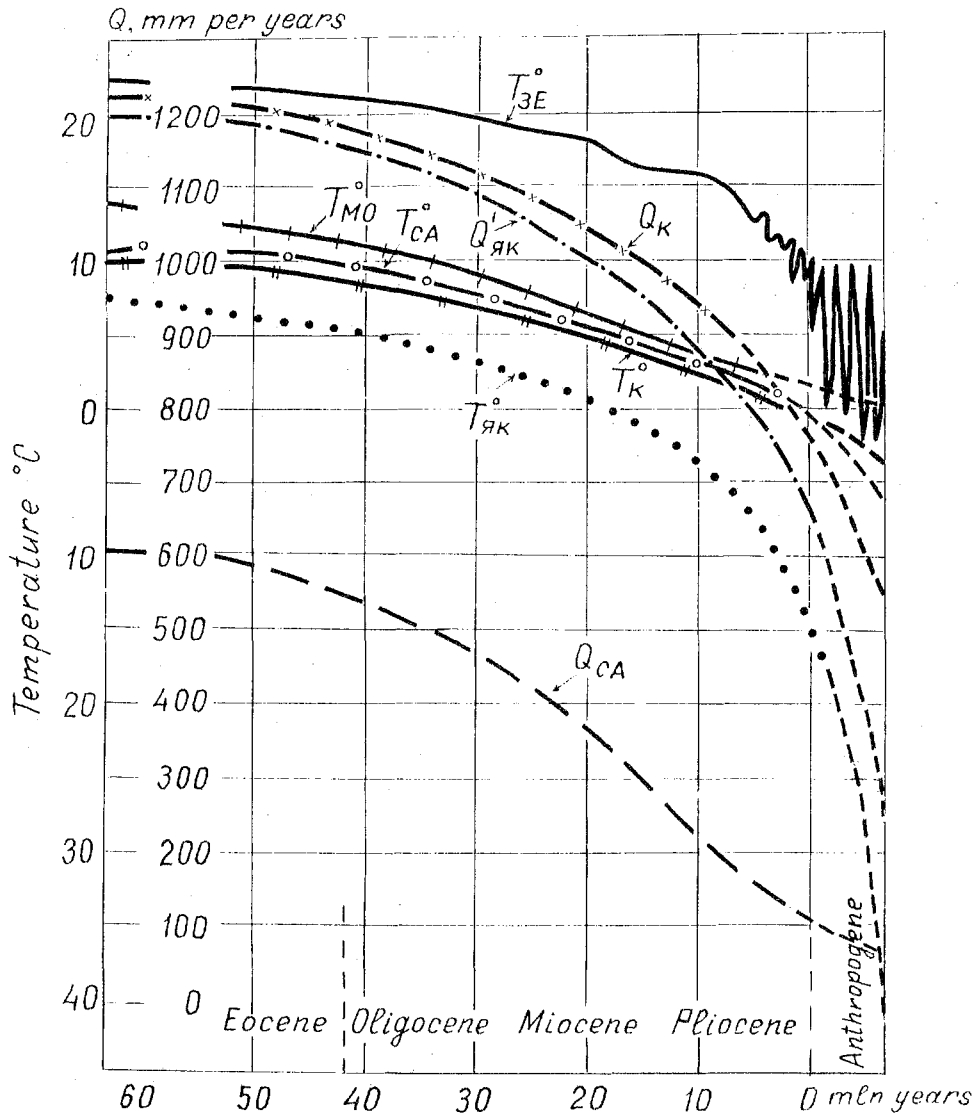


Figure 3. Comparison of the changes of temperatures and precipitation in the Cenozoic period in different points of Eurasia.

Temperatures: $T^{\circ}_{ЗЕ}$ - mean annual in West Europe (after O. Voldshtedt); $T^{\circ}_{МО}$ - near-bottom layer of water of the World Ocean at the equator (after Ch. Emilian); $T^{\circ}_{СА}$ - the coldest month in Soviet Central Asia; $T^{\circ}_{К}$ - the same in Kiev; $T^{\circ}_{ЯК}$ - the same in Yakutsk. Precipitation: $Q_{СА}$ - precipitation in the centre of Soviet Central Asia; $Q_{К}$ - the same in Kiev; $Q_{ЯК}$ - the same in Yakutsk (after V.M. Sinitsyn).

The main feature of the paleogeography of the Pleistocene (from about 2 million years ago up to the present time) were large cycles of glacial and interglacial epochs (Table 3), marked by periodic enlargements of vast ice-masses on continents and in the Polar zone during glacial epochs and by sharp reductions of these masses down to the existing or even smaller sizes during interglacials. Advances and retreats of ice-sheets were accompanied by eustatic fluctuations in the level of the world ocean; it fell by many tens of metres during glacial epochs and rose during interglacial epochs. It is almost generally accepted that such cycles of ancient glaciations were initiated by periodic changes in the amount of incoming radiation 13, 14, 15, 16. It is considered that in low latitudes analogous cycles of pluvial and xerothermal epochs took place. A pluvial time during the glacial period is considered to have been an equivalent of glacial epoch, and an xerothermal one an equivalent of an interglacial epoch. As present investigations show, paleogeographic changes played an important role in the development of hominids and in the progress of the material culture of primitive society 11, 17, 18. During these changes there occurred an anthropological differentiation of hominids, with the formation of blind alleys in the evolution of man (Neanderthal man). Climatic changes within the anthropogenic period apparently caused the first ecological crisis in the history of mankind, and influenced its general progress and regular transition from gathering to hunting, and to development of agriculture and cattle-breeding (Table 4).

Table 3

The scheme of time distribution of the Pleistocene epochs

Sub-Sections	Absolute age, thousands of years	The Alps	Western Europe	Eastern Europe	North America
Upper	50 100	<u>Würm</u> Riss-Würm	<u>Weichsel</u> Eem	<u>Valdai</u> Mikulino	<u>Wisconsin</u> Sangamon
Middle	200 300	<u>Riss</u> Mindel-Riss	<u>Saale</u> Holstein	<u>Dnieper</u> Odintsovo <u>Moscow</u> Likhvino	<u>Illinois</u> Yarmouth
Lower	500 600 700 800 1000	<u>Mindel</u> Günz-Mindel <u>Günz</u>	<u>Elster</u> Cromer		<u>Kansas</u> Afton <u>Nebraska</u>

Underlined are the titles of glaciation epochs.

Table 4

Absolute age (thousands of years)	Man	Material culture	Nature
100	Neanthropes (Neanderthal men)	Upper paleolithic Middle and Lower paleolithic	Würm Riss-Würm Riss
350	Poleanthropes (Pithecanthrope men)		Mindel-Riss Mindel
700	Aerchanthropes	Aeopaleolithic (cultures of	Günz-Mindel
1500	Australopithecus	pebbles and choppers)	Günz

All these events, and their paleoclimatic causes in particular, were discussed at many recent international scientific congresses, conferences and symposia, the proceedings of which are published regularly. We may single out among them the latest congresses of the International Quaternary Association, which were held in Paris (1969), Christchurch (1973) and London (1977); the International Symposium on Quantitative Methods of Evaluation of Climatic Changes during the Pleistocene (Giff-sur-Ivette, 1973); the International Symposium on Long-Term Climatic Fluctuation (Norwich, 1975); and other forums. Of greatest interest are results of latest investigations into these problems described in the works by Emiliani, Morner, Charle, Finck, Flenn, Velichko, Grichuk and other authors.

In the present paper we have not enough space to examine systematically the whole problem of the paleoclimate of the Pleistocene. Possibly there is no need to, since the most important task of modern paleoclimatology is to single out the main time thresholds or key episodes similar to the pre-glaciation epoch (the Mio-Pliocene), which can be valuable in forecasting. Such key episodes, in our opinion, are first, the last warm interglacial period (variously called the Riss-Würm, Aihem, Mikulino, or Sangamon), and second, the coldest stage of the last glacial period (variously called the Upper-Würm, Valdai, or Wisconsin).

The last warm interglacial epoch, which took place 120-75 thousand years ago, was very well expressed globally. Lamb in characterizing the general conditions of this particular interglacial writes [8]: "During the warm land interstadial the ocean level was 18 m higher than it is today, an enlarged Baltic Sea had wide contact with the Atlantic, and with the White Sea through the Danish Straits and the Gulf of Finland. Scandinavia was an island... All northern Europe had a climate more oceanic than that of post-glacial times" (p.335). The corresponding paleogeographical data

were generalized on special maps [19] and these are reproduced in Figure 4. According to these data, continental ice was completely absent from the territory of Europe during the Mikulino interglacial epoch. Almost the whole of the continent was occupied by forests, the boundary of broad-leaved forests being 5-6° further north than it is at present. The tundra was missing, and the steppe border-line was also transferred a long distance to the south-east of Europe.

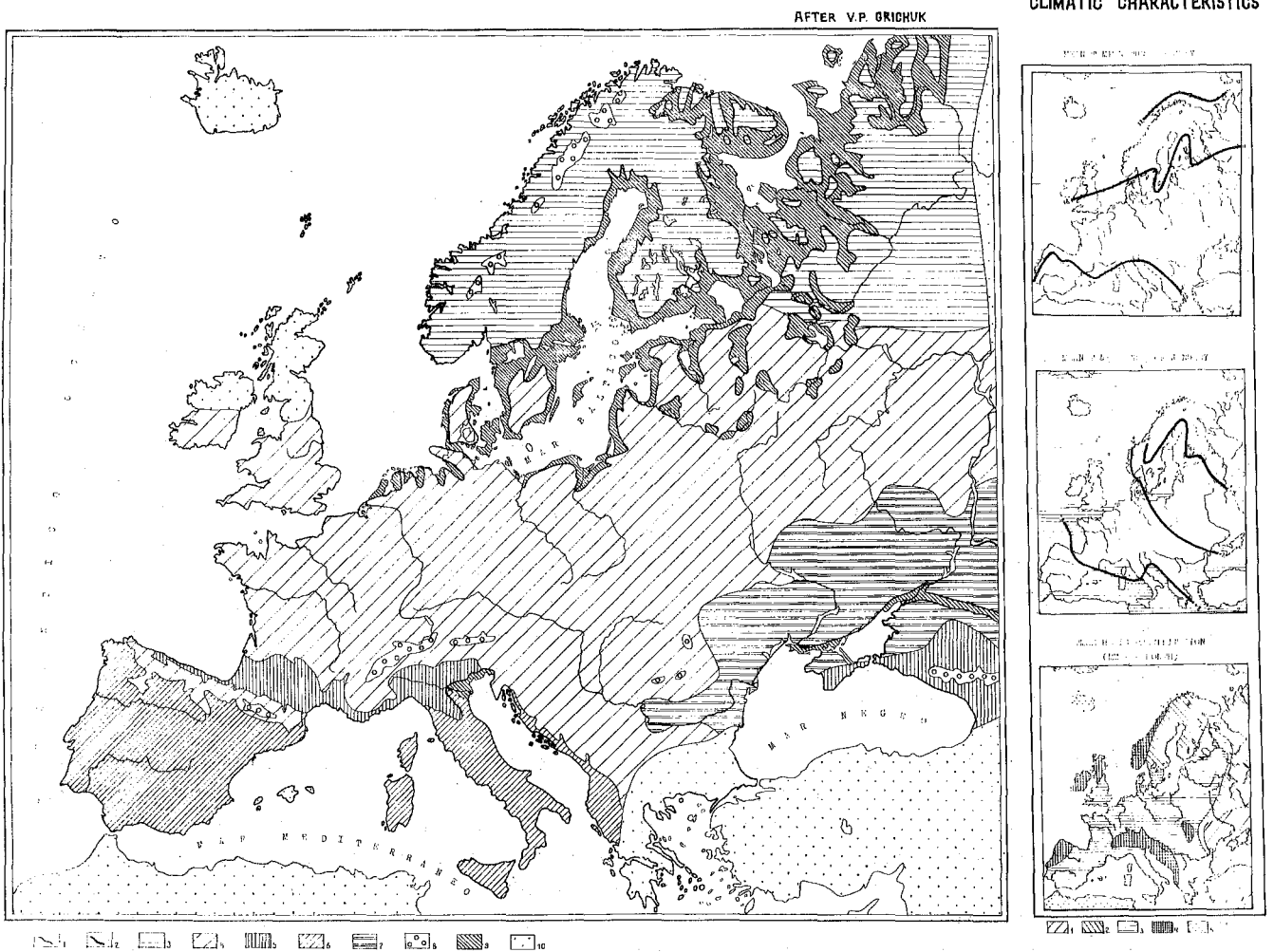


Figure 4. Nature of Europe in the epoch of the last interglacial.

All these data taken together enable us to suppose that the climatic conditions of the last interglacial were intermediate in character between the pre-glacial (Mio-Pliocene) period discussed above and present times. In other words, climate was cooler as compared with the pre-glacial time but still warmer in comparison with that of today. The general character of natural zonation in Europe enables us to suppose that a considerable advance of the maritime climatic region to the east occurred as compared with modern times.

The coolest stage of the whole Pleistocene was, according to all available paleogeophysical data, a late phase of the last glaciation, which covered a period of time from 20-25 thousand years ago up to 10-12 thousand years ago. Velichko ²⁰ called this episode "a third cryogenic stage" of the Pleistocene, which replaced the preceding one - which was "glaciogenic". With this definition, it was emphasized that in the later phase of the last glaciation, the distribution of continental and sea ice was not at its maximum, and that the distribution of permafrost advanced at that time far beyond the limits of glaciation. Figure 5 represents this important feature.

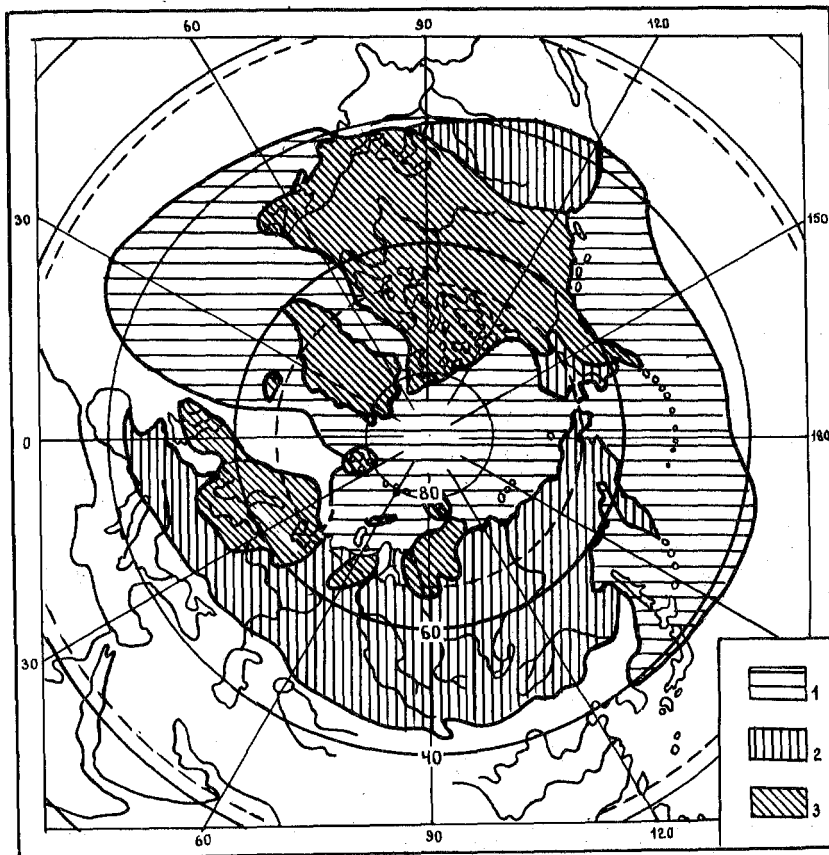


Figure 5. Cryogenic area of the northern hemisphere at the third stage of Pleistocene
1. Sea glaciation.
2. Permafrost.
3. Ice sheet.

The same feature is visible in Figure 6 on which there is represented a reconstruction of nature in Europe at those times. As is seen, the general character of the vegetation cover at the time in question was highly specific, and had no analogous features with the vegetation of modern Europe. Alongside the Scandinavian continental ice-sheet there stretched periglacial birch and leaf-bearing woodland, among which there could be seen incursions of the tundra. To the west this zone merged with tundra and sub-arctic meadows, and to the south it merged with a wide belt of cold periglacial wooded steppe. This entire belt had traces of former development of permafrost, with the mean temperature down to -5 deg. C, and 100-150 m thick. Only regions of Central Yakutia, situated near the cold pole of Eurasia, can be recognized as a present-day analogue of these landscapes. In Table 5 this conclusion is confirmed by comparison of some climatic indices.

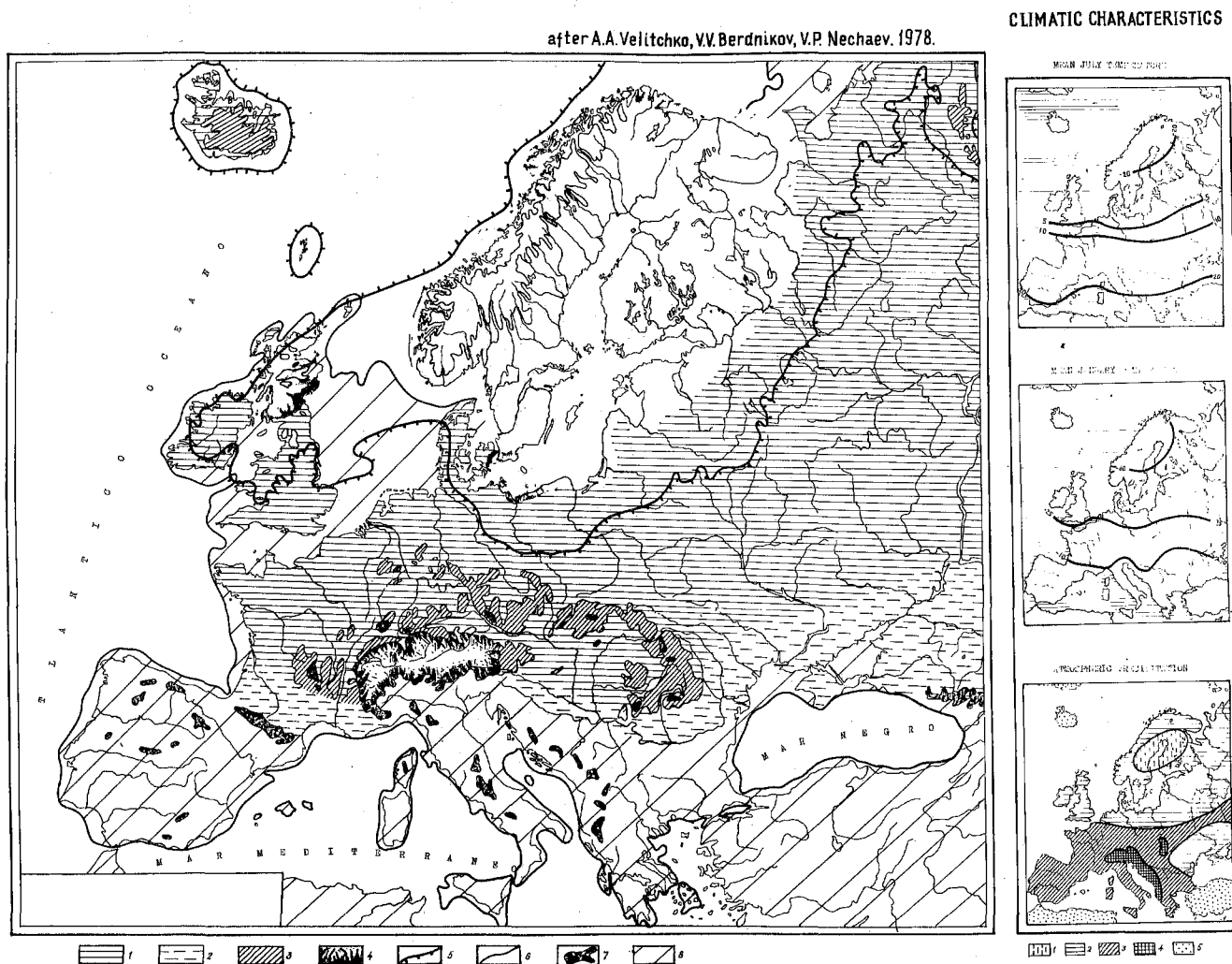


Figure 6. The last glaciation of Europe and its periglacial

Table 5

Time	Temperatures			Totals of atmospheric precipitation per annum
	January	July	mean	
Modern (Bryansk)	-8.5°	18.4°	10°	580 mm
Maximum of cooling (Upper Valdai)	-40 to -45°	16-18°	-10 to -12°	100-150 mm
Maximum of warming (Mikulino interglaciation)	0°	18°	9-10°	600-700 mm
Modern (Yakutsk)	-43.2°	18.7°		

It should be noted that paleoclimatic investigations undertaken by American experts under the CLIMAP programme for the episode in question (15-20 thousand years ago) yielded results quite similar to those described above [21]. These results refer to the North Atlantic area and are based mainly on paleo-temperature data. They are represented in Figure 7, where the distribution of temperature deviation of surface waters of the ocean from contemporary values is depicted. During the Upper Würm these deviations reached a value as high as -10 deg. C.

Proceeding from traditional ideas about appearance and stable condition of anticyclonic climatic regimes over the major ice-sheets and the adjoining frozen area, the paleoclimatic conditions of the coldest phase of the Pleistocene should be regarded as totally different from those of the present. It may probably be assumed that a radical change of the whole system of oceanic and atmospheric circulation took place during the time interval under consideration. Such a change is called by Velichko hyperzonal [20] and he emphasizes that during this episode a great weakening of zonal atmospheric circulation and strengthening of the meridional circulations (as opposed to the interglacial phase) occurred. A hypothetical scheme of such climatic conditions is represented in Figure 8.

After the epoch of maximum cooling (25-12 thousand years ago) and after gradual degradation of the last ice sheets in the Holocene period, there occurred successive changes in climatic phases of the post-glacial epoch. These stages were first established for Scandinavia, but have since been found the world over (Table 6). According to this scheme, within the post-glacial epoch of 11-12 thousand years, one epoch of maximum warming (Atlantic period - 5-8 thousand years ago) occurred, which was preceded and followed by cooler epochs (Boreal and Sub-Boreal periods).

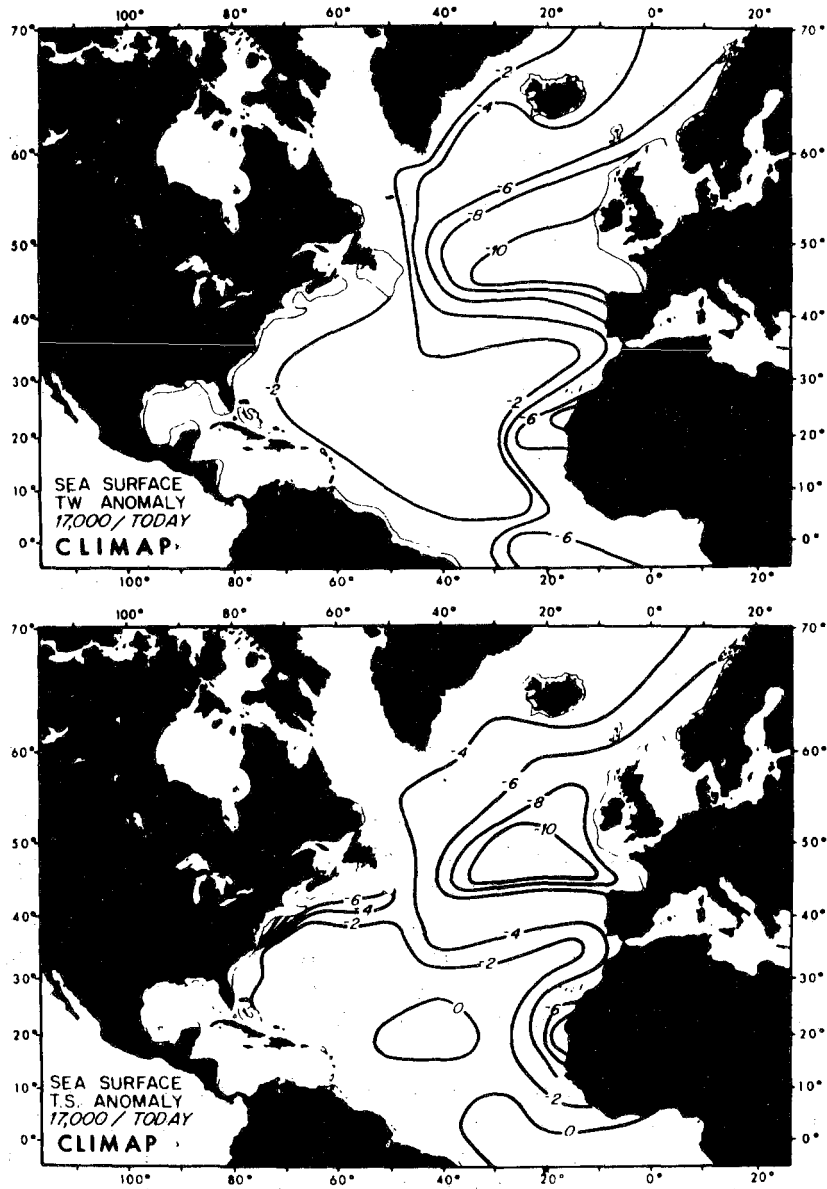


Figure 7. Sea surface temperatures prevailing at the last maximum of glaciation about 15 000-17 000 years ago, as departures ($^{\circ}\text{C}$) from today's values. (Source: 21).

- (a) In winter
- (b) In summer

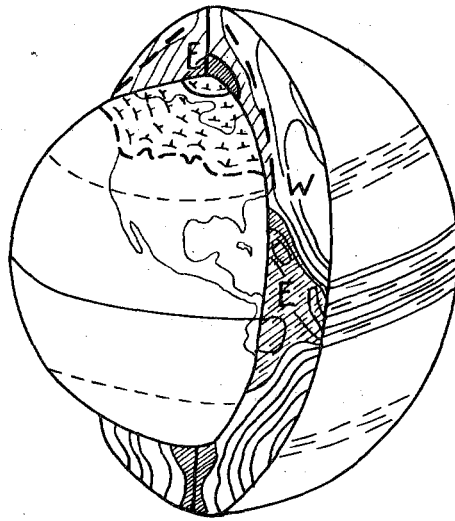


Figure 8. A working scheme of changes in the circulation systems in the troposphere in the winter season during the maximum of the last glaciation as compared with the present time (Velitchko, 1977)

E - systems with predominating easterly transfer of air; W - those of westerly transfer. Shaded area shows the zone of probable expansion of anticyclonic masses of air in the cold time of the year of the Late Pleistocene climatic minimum. Within North America the Late Pleistocene ice sheet is shown.

In the epoch of the maximum of the last glaciation, in the cold time of the year the area of the low level polar anticyclone spread considerably southward, pushing the westerly air stream away from the Earth's surface and approaching the area of high pressure in the sub-tropics. As a result of the above processes, in the greater part of the northern hemisphere in the near-surface layer of air easterly transfer became predominant. This conditioned the spread of low-temperature anticyclonic air masses with low amounts of precipitation, not only in the extra-tropical areas of Asia but in Europe as well. A powerful expansion of the area of permafrost took place in the whole of Eurasia, while ice sheets there were relatively small. At the same time precipitation from the Bermuda-Azores region continued to come to North America, resulting in the development of a thick ice sheet there.

Table 6

Phases of the Holocene period
(the scheme by Blytt-Sernander)

Indices	Absolute dating	Phases	Climate
	12 000	Arctic and Subarctic	Cold
	11 000	(the last Dryas, Allerød)	
PB	8 000	Pre-boreal	Cool at first and dry, then moderately warm
		Boreal	
AT	5 000	Atlantic	Warm and humid
B ₁₋₃	2 000	Sub-Boreal (with subdivisions)	Warm and dry
A ₁₋₃		Sub-Atlantic (with subdivisions)	Cool and humid

An assumption about a possible analogue between the post-glacial (Holocene) period which began 11-12 thousand years ago and the previous interglacial epoch was put forward long ago. From this assumption, it followed that the Holocene, like the interglacial period, is characterized by a definite cycle of climatic changes, from primary cooling to a climatic optimum nearly 5 000 years ago and then again to a new cooling - forerunner of renewed glaciation. In Figure 9 this general representation is verified (for the centre of the Russian Plains), mostly with the help of paleobotanic data. In this figure the course of climatic changes during the last interglacial is compared with that of the Holocene. Such a comparison enables us to suppose that historical time and the contemporary period can be regarded as a transition from the post-glacial climatic optimum (the Atlantic phase) to cooler climatic levels, preceding the beginning of a new glacial period. This transition, of course, is not gradual; it is complicated by periodic epochs of warming and cooling (similar to the so called "short glaciation period" or "Little Ice Age Period"). The general tendency to progressive cooling clearly follows from paleogeographical data.

Approximate calculation of the rate of cooling is possible on the basis of these data. Distinct signs of the beginning of a new glacial epoch can appear within the next thousand years, as suggested by the left-hand arrow of Figure 11. Figure 10 is another representation of the same idea.

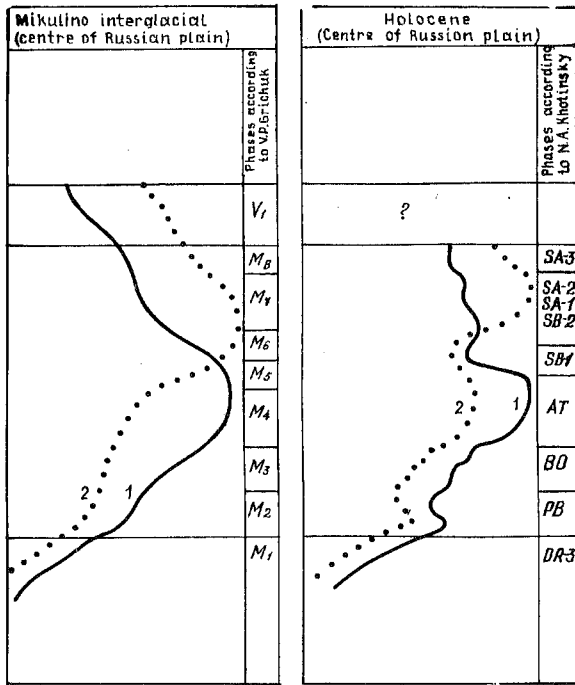


Figure 9. A scheme of the comparison of climatic stages of the Pleistocene rhythm, Mikulino interglacial and Holocene.

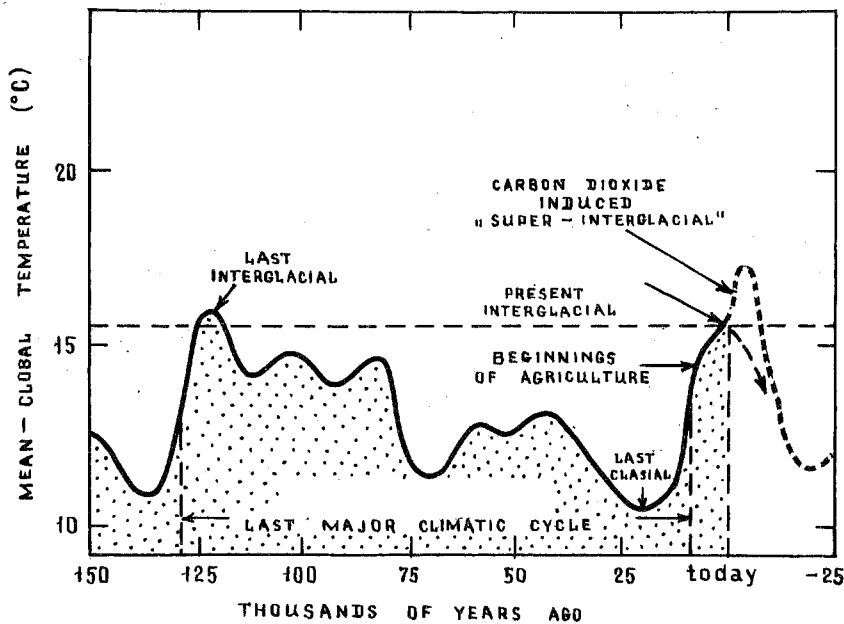


Figure 10. According to a version of the astronomical theory of ice ages [22] the natural course of future climate (shown by the dashed curve) would be a cooling trend leading to full glacial conditions 23 000 years from now. The warming effect of carbon dioxide, however, may well interpose a "super-interglacial", with global mean temperatures reaching levels several degrees higher than those experienced at any time in the last million years. In that case, onset of a cooling trend leading to the next ice age would be delayed until the warming had run its course, perhaps 2,000 years from now (modified from Mitchell [23]).

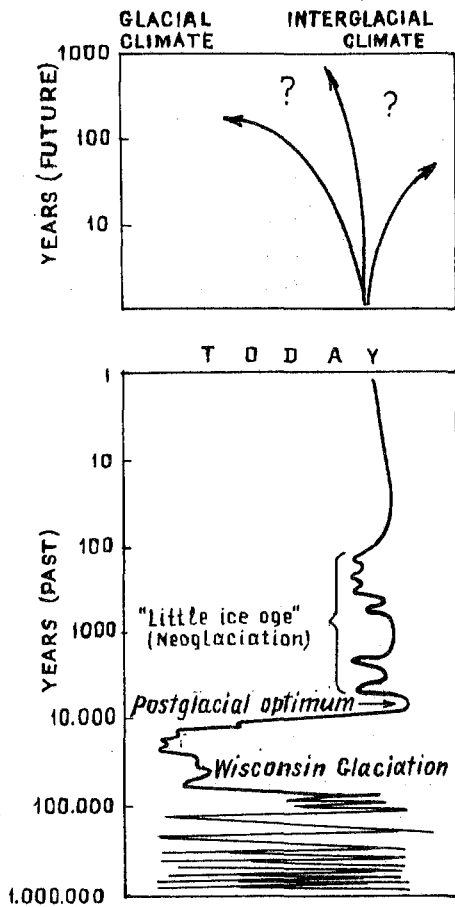


Figure 11. Climatic variability during the past million years, and possible future short-term climatic trends.

There is no reason, however, to conclude this paper with such a pessimistic forecast. Even if we consider the above natural trend of geological change in climate for the future well enough reasoned, in our general forecast we cannot merely be guided by this trend. It goes without saying that contemporary change of climate is more and more determined by anthropogenic influences upon climate-forming factors. Consideration of such influences, of their intensity, degree and time parameters goes beyond the limits of this paper. Nonetheless, it is clear that both the modern and, still more, the future activity of mankind are undoubtedly capable not only of overcoming but even of reversing the natural trends in evolution of climate. In other words, human activity can create preconditions for such climatic situations of local, regional and global scale which may be contrary to the natural flow of events analogous to those former paleoclimatic situations.

As this paper shows, paleoclimatology can offer mankind a choice from a variety of climates of past geological epochs. Most probable among them are the following three variants prompted by geological history: very warm and humid, rather monotonous over large areas, the climate of the pre-glaciation period (Mio-Pliocene); less warm but with great spatial changes, the climate of the interglaciation period; and, lastly, the inbetween or transitional climate following the interglacial, similar to the period up to the present.

Many investigators of anthropogenic changes in climate consider that, under the influence of increasing CO₂ concentration and of other factors in the next few decades, a rapidly progressing change in climate towards a warming will occur. If this process runs unchecked, then the climatic conditions of the last interglaciation period can be overcome swiftly by way of forming a "super-interglaciation period" (see Figure 10). In case the process of anthropogenic warming of climate will be taken under control and become regulated, then the best model to adopt would be an analog of the "pre-glaciation period" (right-hand arrow in Figure 11) with which, however, models of interglacial warm periods such as the post-glaciation climatic optimum could compete.

Hope should be expressed that before a radical change in global climate takes place under the influence of economic activity of mankind there will be found ways of influencing climates which will prevent undesirable changes of the environment and will provide stable optimum climatic conditions over the whole territory of the Earth.

I would like to finish my report with several suggestions as to the main tasks of further paleoclimatic investigations. They are as follows:

1. All possible enlargement of paleoclimatic (paleogeographical) investigations as a necessary foundation for climate prognostic efforts. Alongside a multilateral study of traditional objects (for example, geological deposits with paleobiological remains), special attention should be given to investigation of the thick masses of ancient continental ice sheets (being mindful that the absolute age of ice in Antarctica is determined to be 20 million years), of cave formations with archeological remains, of the bottom deposits in large lakes (an example of such investigations being the work conducted by Japanese scientists on Lake Biwa), and of deep-water deposits in oceans.
2. Further development and use of modern geomorphological, lithological, geochemical, and biological methods of investigation, and specifically of isotope methods of absolute age dating (especially for the interval of 30 000-100 000 years), of geochemical and biochemical methods for determining characteristics of conditions of the environment (for instance: temperatures, salinity, gas composition, etc.), and of paleoecological peculiarities of organisms.
3. Concentrate attention on five time intervals of the most importance for prognostic studies: the preglaciation (12-2.5 million years ago); the last interglaciation period (50-100 thousand years ago); the last glaciation period (18-20 thousand years ago); the climatic optimum of the post-glaciation period (5-8 thousand years ago); and of the so-called "Little Ice Age" epoch (1 500-1 800 A.D.).
4. Wide use - as the basic method for summing up of regional data - of paleogeographical reconstruction in the form of maps and atlases for the key-regions (Europe, Siberia, Far East, Canada and USA, the Mediterranean Sea region, East Africa, Central Asia, South-East Asia, Australia, North and South Atlantic, the Pacific and Indian Oceans) with maximum filling in of quantitative characteristics. With international scientific co-operation there should be organized generalisations of these regional materials for the northern and southern hemispheres separately and for the globe as a whole for these, the major periods of interest for prognostic studies (see text above).

5. On the basis of paleogeographical maps and atlases and of the general theory of climate to work out conceptual and quantitative models of former climates together with their climate-forming processes to serve as probabilistic prognostic tools.

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THE PHYSICAL BASIS OF CLIMATE

W. Lawrence Gates*

1. Introduction

Most of us probably take the climate where we live for granted, and have given little thought to either the fact that it has not always been the same or to the likelihood that it will change in the future. To the scientist, however, the climate of the Earth represents a challenging problem in geophysics as he seeks to understand the physical processes which are responsible for its structure and variation. From the study of past climates, we know that most regions of the Earth have undergone a long and complex history of climatic change, but how these bits of evidence fit together remains an unsolved puzzle. There is at the present time no unifying general theory of climate, and it is therefore not surprising that there is great uncertainty in the prediction of climate changes and even uncertainty over the extent to which the future climate may be predicted at all.

Man long ago learned to adjust his activities to the average regimes of rainfall and temperature found in various parts of the world. This adaptation to the climate is so much an accepted part of life that we are only made aware of the extent of modern man's dependence upon climate by the advent of an unexpected change such as a drought or an unusually severe winter. Man's response to a change of climate is determined not only by its location in relation to his climate-sensitive activities such as agriculture, but also by the speed or rate at which the change occurs. If the climate did not change perceptibly, man could easily reach a stable climatic adjustment and interest in the climate would not extend beyond the collection of the necessary geographical statistics. But the climate - for better or worse - is not constant, and man is continuously faced with the need to adjust to a seemingly endless series of climatic changes which at the present time he can neither forecast accurately nor fully understand.

The experience of the last few years, which have brought unusual climatic changes in many parts of the world, was sufficient to convince most people (and their governments) that even a temporary change of climate has profound impacts on agricultural production and on the use of energy and water resources. It is this anticipation or prospect of a changing climate which is responsible for the upsurge of interest in the climate problem. Like all other phenomena in nature, however, the

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climate and its changes are presumably governed by physical laws, and the discernment of those laws is the goal of modern climate research. This represents the most rational approach to the problem, and the possibilities of scientific climate prediction and control rest directly upon our understanding of the physical processes involved.

The popular notion of climate as the averaged weather, supplemented perhaps by some information on the occurrence of extreme or unusual events, is also used by the scientist. But while weather is concerned with the daily progress of such familiar events as wind, clouds, rainfall and temperature, the climate is concerned with their longer-term statistics. The climate in a particular location therefore depends upon the time interval used to average the weather, and is generally not the same over every year, decade or century. In a general sense therefore, the physical basis of climate includes the physical basis of weather.

But in addition to the average behaviour of the atmosphere, the scientific definition of climate also includes the average behaviour of the oceans, the behaviour of the world's ice masses, and the condition or state of the land surface and its associated vegetation. Each of these elements is linked together in a worldwide system, with changes in one part generally affecting the behaviour of other parts and setting in motion a chain of effects which may either reinforce or cancel the original change. The number of possible mechanisms causing changes of climate is therefore rather large, and the observed variations of past climate represent the attempts of the system to reach equilibrium. Because the ocean, however, changes much more slowly than does the atmosphere, while the ice fields and the character of the land surface and vegetation change even more slowly, it appears that the climate never reaches a true steady state, and is destined forever to oscillate between one extreme and another. These changes are so slow as to be almost imperceptible compared to the daily changes of weather, but over hundreds and thousands of years they can produce climates as different as the present summer and winter. The spectrum of climate change is made even broader by the influence of factors outside the atmosphere and ocean, such as astronomical changes in the radiation from the sun and changes in the distribution of the Earth's oceans and continents over geological time.

The climate and its change hang in the balance among such processes, and this accounts for the fact that the climate may be changing in different ways and at different rates in various parts of the world at the same time. Unravelling the course of these changes and organizing their characteristics in terms of physical causes is the scientific challenge of the climate problem. In this paper I shall attempt to describe this problem in terms of the physical processes involved, and to summarize both the origins and limitations of our present understanding of the mechanisms of climatic change.

2. The climatic system

Having noted that, in addition to the atmosphere, the climate involves the oceans and other surface waters, the world's ice masses, and the surface soil and vegetation, these physical entities may be conveniently grouped into the components of the climatic system [1, 2]. Thus, the climatic system consists of the atmosphere (comprising the Earth's gaseous envelope and its aerosols), the hydrosphere (comprising

the liquid water distributed on or beneath the Earth's surface), the cryosphere (comprising the snow and ice on and beneath the surface), the surface lithosphere (comprising the rock, soil and sediment of the Earth's surface), and the biosphere (comprising Earth's plant and animal life, and, by extension, man himself). Each of these components has quite different physical characteristics, and are linked to each other and to conditions outside or external to the system by a variety of physical processes as shown in Figure 1.

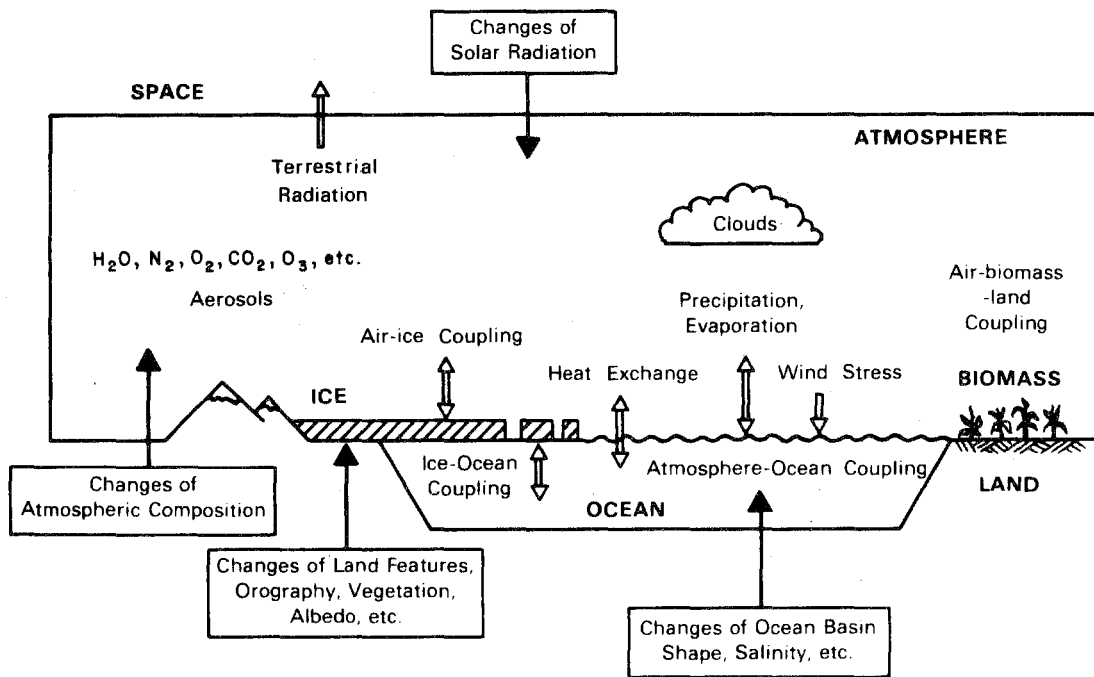


Figure 1. Schematic illustration of the atmosphere-ocean-ice-land-biomass climatic system, with some examples of physical processes responsible for climate and climatic change. Sources /1, 2/

The atmosphere is of course the central component of the climatic system, and displays a spectrum of climate ranging from the microclimates of local sites to the climate of the entire planet itself. For many of man's activities the most important elements of the atmospheric climate are the seasonal regimes of temperature and precipitation, and it is on this basis that the world's climates have traditionally been classified. The global distribution of such climatic zones or types shows the familiar warm and moist climates of low latitudes, generally warm and drier climates in the subtropics, the generally temperate climates of midlatitudes, and the cold and dry climates in the higher latitudes. The detailed geographical distribution of climatic types clearly reveals the ocean's moderating influence on seasonal temperature changes, and shows the extremes of both temperature and precipitation introduced

by mountains. The statistics of other atmospheric variables, such as sunshine, cloudiness, humidity and wind, are also of critical importance in many activities such as energy generation and the use and the management of water supplies.

The atmosphere may generally be expected to respond to an imposed change more rapidly than do the other components of the climatic system. This is due to the gaseous atmosphere's relatively high compressibility and its relatively low specific heat, which combine to make the atmosphere more mobile and more likely to become unstable. The time-scales or lifetimes of the atmosphere's response range from a few minutes or hours in the case of local convective motions to a few days in the case of the large-scale transient cyclones and anticyclones of middle latitudes. Such phenomena play an important role in climate as well as weather, and are in turn regulated by the atmosphere's structure and circulation on other scales. For example, the familiar afternoon maximum of temperature and, in many locations, of convective clouds and rainfall, is due to the diurnal variation of the surface heat budget, while the characteristic seasonal regimes of weather are due to shifts of the global-scale circulation in response to the seasonal changes of solar radiation. Since these diurnal and seasonal phenomena display greater amplitude in the atmosphere than do their counterparts in other components of the climatic system, the atmospheric climate is characterized by relatively large synoptic- and seasonal-scale fluctuations about the climatic mean. The atmosphere's response may also be characterized in terms of the time which would be required to generate (or dissipate) typical atmospheric temperature and motion patterns in response to typical rates of heating and typical frictional forces. This time is estimated to be about one month, which we note is longer than the lifetime of an individual atmospheric cyclone but shorter than a season.

The hydrosphere is a close second to the atmosphere in terms of its overall importance in the climatic system. The extent and bulk of the world's oceans and the prevalence of surface water on the land insures a potentially plentiful supply of water substance for the global hydrological cycle of evaporation, condensation, precipitation and runoff. Once in the atmosphere, water substance in vapour, liquid or solid form continues to play an important role in climate through its selective absorption and/or reflection of both solar and terrestrial radiation.

The climate of the hydrosphere itself consists of the distribution of the temperature, salinity and velocity of the oceans and land surface waters. In comparison with the atmosphere, this liquid portion of the climate system is relatively unexplored, although the oceans appear to play a major if not a dominant role in most changes of climate. Since the oceans cover approximately two-thirds of the Earth, most of the solar radiation reaching the surface falls into the ocean where it is absorbed by the uppermost few metres of water. Because of the high specific heat of water this absorbed radiation results in a relatively small change in the ocean's temperature compared to that which would occur over land. The oceans therefore act as a heat reservoir, and slowly transport their heat by ocean currents from the equatorial and tropical regions (where more heat is received from solar radiation than is lost through back-radiation from the ocean's surface) toward the generally colder middle-latitude and polar regions. This oceanic advection process requires years to complete, and is therefore much slower than the corresponding heat transport effected by the atmosphere's circulation on time scales of weeks. Recent observational evidence indicates that the oceans may in fact transport more heat poleward at some latitudes

than does the atmosphere. A portion of the heat stored in the ocean's surface water is released to the atmosphere through direct conduction in those regions where the ocean is warmer than the overlying air, and a portion is used to evaporate water into the atmosphere.

Like the atmosphere, the ocean is free to move in response to heat exchanges at the surface. But unlike the atmosphere, it is local surface cooling rather than heating which initiates convective motions in the ocean. The depth to which such vertical overturning extends depends upon the magnitude of the surface cooling and upon the ocean's local vertical density stratification, and these same factors therefore determine the time scales on which ocean water at various depths is in effective communication with the surface. The surface mixed layer which is present in the top 100 m or so over most of the world's oceans responds to changes of surface heating on synoptic time scales, while the thermocline found at several hundred metres depth responds to seasonal changes in the surface heat budget. The deeper water, which comprises the bulk of the ocean, responds even more slowly due to its relatively large thermal and mechanical inertia, and reacts to changes of surface conditions on time scales of decades and centuries as shown in Figure 2.

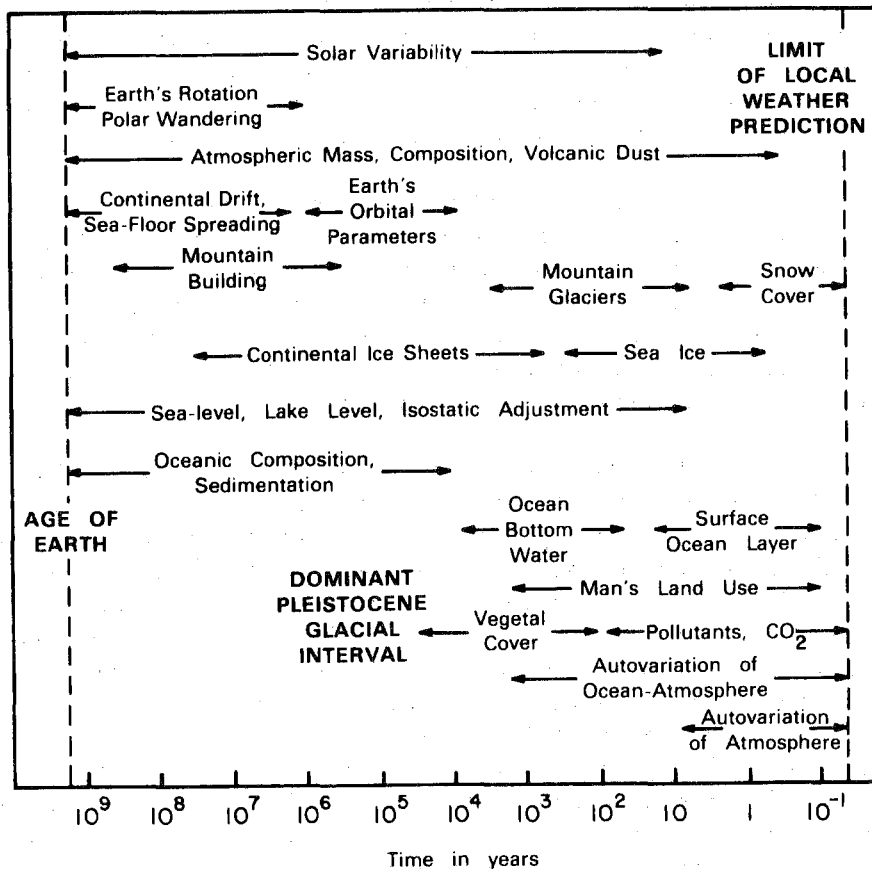


Figure 2. Characteristic events and factors in climatic change over various time scales in the atmosphere, hydrosphere, cryosphere, lithosphere and surface biomass. Source: 18

The cryosphere, like the hydrosphere, consists of a portion closely associated with the sea (sea-ice) and portions associated with the land (snow, glaciers and ice sheets). The importance of the cryosphere to the climatic system lies more in connexion with its high reflectivity (or albedo) and the low thermal conductivity of snow and ice than with its role as fresh water storage. When snow covers land or when a layer of sea ice forms on the ocean, the surface albedo is greatly increased, and because snow and ice are such good insulators, heat exchange with the underlying land or ocean is also reduced. These effects in turn tend to induce a colder local climate through the reduction of the net surface heating. In the northern hemisphere a considerable portion of the land is covered by snow and ice each winter, while in the southern hemisphere the ice pack surrounding Antarctica undergoes a dramatic winter-time expansion.

In addition to these seasonal cryospheric changes, significant variations also occur over much longer periods. In response to gravity, the ice in a mountain glacier moves slowly downward and outward, and over a century or so may either greatly expand its area or disappear altogether, depending upon the local snow accumulation and temperature. Glaciation also occurs on continental dimensions in the form of ice sheets, and those now covering much of Greenland and Antarctica, and those which have covered parts of Europe and North America in times past, have lifetimes of tens of thousands to millions of years, depending upon whether the climate (which the ice sheets themselves help to determine) is favourable or unfavourable for their maintenance. Extensive ice masses may also have an indirect influence on climate by lowering the level (and hence reducing the area) of the sea during periods of extensive glaciation.

The surface lithosphere, in contrast to the atmosphere, hydrosphere and cryosphere, is a relatively passive component of the climatic system. Even though the diurnal, synoptic and seasonal variations of temperature over land are greater than those over water, the physical characteristics of the surface soil and rock are usually taken as fixed elements in the determination of the climate. An exception to this is the amount of moisture in the surface soil, which is closely related to the local surface and ground hydrology. Such soil moisture exerts a marked influence on the local balance of moisture and heat at the surface by its influence on the surface evaporation rate and on the soil's albedo and thermal conductivity.

On time scales of hundreds to thousands of years, the character of the land surface is itself determined to some extent by the regimes of surface temperature, rainfall and wind. The formation of soil and its destruction through desertification, for example, are surface manifestations of the prevailing climate. On even longer time scales, the topography of the Earth's surface, including the distribution of the oceans and continents, is determined by geological processes over tens to hundreds of millions of years. The climate on these time scales must have been profoundly affected by the changing shape of the world's ocean basins and as mountains arose as a result of continental drift. The periods of major glaciation during the Earth's history also appear to have been periods when continents were beneath the Earth's rotational poles, and may also have been periods of major volcanic activity.

The remaining component of the climatic system - the surface biomass - interacts with the other components primarily on time scales which are characteristic of the life cycles of the Earth's vegetative cover. Most prominent among these is the seasonal cycle of plant growth in response to the seasonal variations of solar radiation, temperature and rainfall. The trees, plants and ground cover in turn modify the surface radiation balance and the surface heat flux, and play a major role in the seasonal variations of local surface hydrology. Such biospheric effects are at a minimum in desert regions, although there is evidence that the stability and lateral extent of the deserts themselves are influenced by the vegetation in the surrounding areas. Over time scales of hundreds to thousands of years, the surface biomass is known to be closely linked with the prevailing atmospheric and hydrospheric climate, and the record of fossil species as preserved in soils and sediments and the record represented by the varying widths and composition of tree rings are an important source of evidence of the progression of ancient climatic regimes.

Although sometimes not considered a part of the climate system, many of man's activities have significantly altered the Earth's vegetative cover and hence interfered with the natural biospheric component of climate. Over time scales of hundreds to thousands of years, man's land clearing and his agricultural and grazing practices have changed the character of large portions of the Earth's surface, and may have had a greater effect on climate than has the more recent (and more publicized) urbanization.

3. The physical processes of climate and climatic change

The response times of each component of the climate system as discussed above are the result of the physical processes which dominate the behaviour of that component. In the case of the atmosphere and ocean - the more mobile components of the system - these processes include the transfer of fluid properties such as momentum, temperature and suspended or dissolved constituents by both large-scale motions (advection) and small-scale turbulent motions (diffusion), vertical overturning as a result of hydrostatic instability (convection), the selective absorption and emission of radiation, and (in the case of the atmosphere) the release of latent heat accompanying condensation. The occurrence of these processes in the ocean and atmosphere is in turn regulated by characteristic dynamical motions such as local convective circulations, inertia-gravity waves, and large-scale synoptic and planetary waves. These motions are the fluids' natural responses to the forcing represented by the sources and sinks of momentum and heat and have amplitudes which are controlled by the dimensions and physical properties of the fluid. Together with the rotation of the Earth, these properties basically determine whether the climate is dominated by convective circulations (as in lower latitudes) or by transient baroclinic disturbances (as in middle and higher latitudes). In this sense we may regard the local distribution of the oceans and water sources (hydrosphere), land and sea ice (cryosphere), continental topography (surface lithosphere) and surface vegetation (biomass) as combining with the large-scale atmospheric circulation to determine the climate on continental and regional scales.

3.1 Atmosphere-ocean interaction

The physical processes responsible for the maintenance of climate may also be viewed in terms of those which act between the various components of the climate system. Of particular importance among such coupling or interaction processes are those involving the exchange of heat and momentum between the atmosphere and ocean as illustrated in Figure 3.

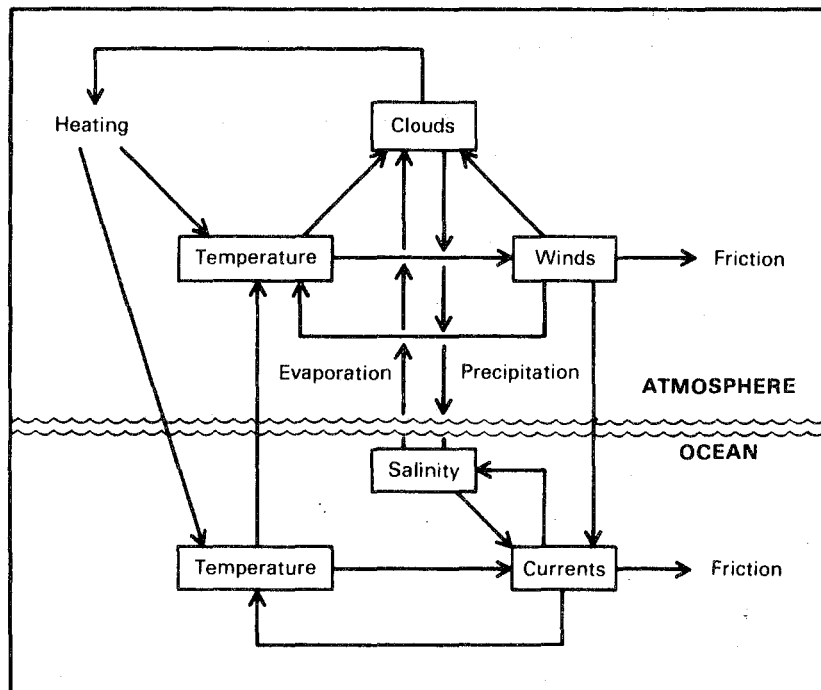


Figure 3. The major physical elements and feedback processes of the coupled atmosphere-ocean system. Source: 18

As noted previously, the surface layers of the oceans absorb most of the solar radiation reaching the Earth's surface, and in turn much of this heat is transferred to the atmosphere. The larger part of this ocean-atmosphere heat exchange occurs as evaporation, which represents a latent heat transfer from the ocean to the air which is subsequently realized at the site of condensation or cloud formation. This flux is effected by the turbulent motions in the lower atmosphere and is dependent upon the surface air's humidity (or low-level vertical moisture gradient) and the surface wind speed. Depending upon the temperature of the surface air in relation to that of the surface itself (or the low-level vertical temperature gradient), these turbulent motions also effect a transfer of sensible heat between the ocean surface and the overlying air. There are similar transfers of heat and moisture between the atmosphere and land surfaces as a function of the land surface character, roughness and vegetative cover, and between the atmosphere and snow- and ice-covered surfaces (see Figure 1).

The transfer of momentum between the atmosphere and ocean consists primarily of a turbulent frictional flux from the more rapidly moving atmosphere to the underlying surface. For the atmosphere this surface frictional drag represents the principal mechanism for the dissipation of kinetic energy but for the oceans it represents the major driving force for the system of large-scale currents which are in turn regulated by frictional processes within the oceans. Ocean currents may also be produced by variations of temperature and salinity, which are in turn tied to atmospheric processes as indicated in Figure 3.

Since the atmosphere and ocean are the only components of the climatic system which are free to move, their interaction is of fundamental importance to the system's behaviour. The ocean and atmosphere jointly accomplish the required poleward transports of heat and momentum, and the ocean's apparent share of these transports has been revised upward in recent years as new observational data have become available. From this point of view, the ocean may play a greater role than the atmosphere in determining climatic variation. Moreover, their mutual interaction may produce internal or auto-variations over time scales of centuries as indicated in Figure 2, even when external conditions are unchanged.

3.2 External influences and climatic history

The complete climatic system may be regarded as a single physical system whose behaviour is subject to a set of geophysical conditions outside the system. From this viewpoint, the external or boundary conditions of the climatic system are the astronomical and seasonal variations of solar radiation at the top of the atmosphere, the composition of the atmosphere, the size, mass and rotation rate of the Earth and the topography of the Earth's crust, including the distribution of mountains and the geometry of ocean basins (see Figure 1). These "external" conditions have themselves changed markedly over the course of the evolution of the planet Earth, with a consequently profound influence on the evolution of climate during the Earth's history (see Figure 2). Without the oceans, the Earth's atmosphere would probably not have evolved into its present oxygen-rich state nor would the atmosphere contain the water vapour necessary to provide nourishing amounts of rainfall. Recent observations have shown that the other planets have not been as fortunate: the atmosphere of Venus, for example, consists largely of carbon-dioxide gas at very high temperatures and pressures, with an almost complete overcast of sulphuric acid cloud, while the thin and cold atmosphere of Mars is also principally carbon-dioxide with large amounts of suspended dust. These climates have evolved over billions of years and, like the Earth's, may either ameliorate or assume further harshness with the passage of future eons.

For a given configuration of external conditions, there may be several possible climatic states (see Section 4.2) and the climate may also depend upon the time evolution of the external conditions. Whether or not this is so, the Earth has necessarily experienced a unique climatic history. The oldest climatic indicators (or proxy data) cover the past several hundred million years or so and come from a variety of biological and geological sources. The distribution of prehistoric species of plants and animals, and the formation of extensive deposits of coal and oil, are clear evidence that at least some climates were somewhat warmer and wetter than those now observed. This period was also one during which the oceans assumed their present

locations through the process of sea-floor spreading, as a result of which the Earth's climates must have undergone substantial changes even though the atmosphere itself may not have been greatly different. During the last million years or so (the Pleistocene epoch), further evidence of the nature of past climates comes from the layered structure of the sediments on the ocean floor and in the surviving ice sheets of Greenland and Antarctica.

By analysing the present distribution of surface-dwelling marine micro-organisms, species which thrive only when the surface water is within certain temperature ranges have been identified. By comparing the relative abundance of their fossils found in the layers of sediment laid down at known times, the record of temperature variations at the ocean surface can be reconstructed over the last several hundred thousand years. These can then be used along with other paleoclimatic data to reconstruct the climate at selected times in the past.

Additional clues to paleoclimate are provided by the observation that the isotope O^{18} is not as readily evaporated as is O^{16} , and hence the water vapour which evaporates from the ocean has a lower O^{18}/O^{16} ratio than does the surface water itself. Since this water vapour is the moisture source of the world's ice sheets and glaciers (whose eventual melting returns the water to the ocean), the ocean surface water will have a relatively high O^{18}/O^{16} isotope ratio at times when there is a relatively large global volume of ice. This isotopic ratio, however, is also picked up by planktonic marine organisms as they build their carbonate shells from the ocean's oxygen, and as they sink to form sediment on the ocean floor they carry with them a virtual tape recording of the timing of the ice ages.

These sources of "proxy" climatic data combine to yield a picture of climatic variation over the last million years which is dominated by the occurrence of ice ages about every 100 000 years. This interval is very close to the cyclic period of the variation of the eccentricity of the Earth's orbit about the Sun, over which astronomical forces (principally the gravitational attraction of Jupiter) cause the orbit to oscillate between the present elliptical shape and a nearly circular configuration every 100 000 years. These forces also cause the obliquity or tilt of the Earth's axis of rotation to change from low to high values and then back again every 41 000 years, and cause a precession of the seasons (or a change in the date when the Earth is closest to the Sun) with a period of about 23 000 years. The present tilt of the Earth's axis ($23\frac{1}{2}^\circ$) is intermediate between its extreme values. Cooler summers (and therefore less melting of ice) tend to be favoured when the tilt is small. These periods are also close to those found in the records from ice and deep-sea cores, and have provided virtual confirmation of the theory that such astronomical or geometrical changes could effect the climate even though the Sun's radiation itself remains constant [3]. On this basis, the Earth appears destined to enter another ice age sometime during the next few thousand years, unless other factors intervene (see overview papers by Hare, Gerasimov and Flohn).

Because of the complexity of the climatic system, it has proved convenient to focus on one portion of the internal system at a time. This portion is then temporarily regarded as the sole internal component, with all other components considered to be part of an external system of known behaviour. Thus, over time scales of months and seasons the atmosphere is commonly considered as the sole internal component of

the climatic system, with the ocean, ice and land surface treated as boundary conditions. When the time scales of interest extend over years to decades, the atmosphere and ocean should be considered together as internal components, while over longer periods the ice, land surface character and biomass must also be treated as variable rather than fixed portions of the system. Aside from simplifying the mathematical treatment, this procedure leads to the identification of each of the conditions or processes which influence the climatic system as possible causes of climatic change (see Figure 2).

3.3 Definition of climate and climatic change

In the analysis of the climatic system, it is useful to develop a scientific definition of climate. From the above discussion, it is clear that such a definition should apply to any or all components of the system and should be applicable over a wide range of time scales. A logical definition of climate would therefore be the complete statistical description of the state of the internal climatic system over a specified time period, together with a description of the state of the external system or boundary conditions. Such a description may then conveniently be called a climatic state and includes not only the familiar time averages of the various physical variables of climate, but their variances and higher-order statistics as well [1]. We may thus identify individual monthly, seasonal or annual climatic states of the atmosphere, for example, in terms of the averages, variances and other statistics of atmospheric variables over these periods, with the accompanying oceanic, cryospheric and land surface data regarded as boundary conditions. The conventional 30-year climatological averages are therefore a special case of such a climatic state for the atmosphere, although even here many of the statistics needed to define the climate completely are unavailable over many regions of the world. The state of the complete climatic system requires similar data for the hydrosphere, cryosphere, land surface and biomass as well. Such statistics have generally not been assembled in a systematic fashion.

This interpretation of climate permits us to define a climatic variation or climatic change as the difference between two climatic states of the same kind, such as the difference between the climate of two Januaries or between the climate of two decades. Since the description of each climatic state includes the means, variances and other statistics for the particular time period selected, a climatic variation will also in general include a change of the variance and other statistics as well as a change of the time averages themselves. In some cases a change of the variance may be a more important aspect of climatic variation than a change of the average itself. We may also introduce the concept of a climatic anomaly (defined as the departure of a particular climatic state from the average of a number of such states, such as the climatic anomaly of a particular January) and also the concept of climatic variability (defined as the variance among a number of climatic states of the same kind, such as the variability of January climates).

Although there are many other meanings in use, the definition of climate and climatic variation over arbitrary time periods (of a month or longer) is especially useful in practical climatic work, and makes more precise the common notions of climate and its changes. Our observations of the atmosphere, ocean and other parts of the climate system are necessarily made over specific time periods, and the assembly and

analysis of data over these times or states are both convenient and natural. We may also note that the simulated climatic data furnished by physical and mathematical climate models (see Section 4) likewise apply to specific time periods, and each such solution or integration therefore defines particular climatic states which may be compared with those observed.

3.4 Characteristics of climatic change

From the preceding discussion it is seen that the physical processes responsible for the maintenance of climate are also those responsible for climatic variations. Although our understanding of the physical basis of climate may be considered reasonably satisfactory (in the sense that we can at least identify the processes involved), we have only limited knowledge of how or why certain of these processes interact to produce a change of climate /1, 2, 4/. The traditional method of studying climatic change has been through the assembly and analysis of observational data and has provided our knowledge of the distribution of present and past climates over the Earth. These data may also be used to estimate the statistical likelihood or probability of future climatic changes on the time scales of the data themselves. Such an actuarial approach necessarily assumes, however, that the statistics of future climatic changes will resemble those of the past.

The large number of interrelated physical processes acting at different rates within and between the components of the climatic system makes the identification of the cause of a climatic variation a difficult task. It seems likely that there is no single cause in most instances and that the relative importance of different effects depends strongly on the time and space scale of the climatic states being considered. For example, interannual differences in sea-surface temperature may be related to the variations of local and regional atmospheric circulation, while the interannual differences in the extent of mountain glaciers are probably not. On the other hand, changes of continental glaciation are related to variations in the Earth's orbital parameters over periods of tens to hundreds of thousands of years, as has been discussed above, and are therefore related to changes of global sea-surface temperature over similar time periods. Climatic variations, however, may also occur as the result of changes in the effective internal driving mechanisms, with no change in the external conditions (the "autovariations" of Figure 2). The inherent irregularity of the weather itself is sufficient to insure that these driving mechanisms will not operate in a perfectly smooth or cyclic way, and the result is the typically irregular records of climate noted earlier.

It is characteristic of climatic change that two (or more) variables of the system are involved in a coupling or mutual compensation. Such interactions or feedback mechanisms may act either to amplify the value or anomaly of one of the interacting variables (positive feedback) or to damp it (negative feedback). For example, the snow cover albedo-temperature feedback is a positive feedback process in which an increase of snow (or ice) extent increases the surface albedo and thereby contributes to a lowering of the surface temperature. This in turn (all else being equal) may lead to a further increase of the extent of snow or ice, reinforcing the initial anomaly. Another familiar example of a positive feedback process is the water vapour-temperature feedback, in which an increase of the amount of water vapour (or absolute humidity) increases the absorption of long-wave radiation and thereby contributes to

a warming of the atmosphere. This in turn may result in increased evaporation and an augmentation of the initial humidity anomaly even though the relative humidity may remain nearly constant. This positive feedback operates virtually continuously in the atmosphere and, along with CO₂, is responsible for the well-known greenhouse effect.

An example of a negative feedback is the coupling between sea-surface temperature and the surface circulation in both the ocean and atmosphere. In this feedback a warm anomaly of sea-surface temperature induces a local atmospheric warming and a consequent lowering of the atmospheric surface pressure. This in turn induces a local cyclonic atmospheric circulation which serves to deflect the surface water outward and away from the initial anomaly through the action of the surface wind stress. An upwelling effect follows in which generally colder water beneath the surface is brought upward to replace the diverging warmer surface water with the result that the initial sea-surface temperature anomaly tends to be dissipated. This feedback illustrates the characteristic conservatism of climatic change mechanisms which involve the ocean.

While we know of many such feedbacks in the climate system, it is likely that there are others yet to be identified. All such feedbacks, however, represent a considerable simplification of the actual sequence of events, and the key phrase in their description is "all else being equal". In a system as complex as climate this is usually not the case and an anomaly in one part of the system may be expected to set off a whole series of adjustments, depending on the nature, location and size of the initial disturbance. The difficulty of tracing such adjustments makes the net effect of individual feedback processes notoriously uncertain in most cases, although they often serve as the motivation of more quantitative diagnostic and modelling studies [5]. We should also recognize that any positive feedback must be effectively checked at some level by the intervention of other processes, or the climate would exhibit a runaway behaviour.

Climatic change may therefore be viewed as an adjustment among compensating feedback processes, each of which behaves in a characteristically nonlinear fashion. The fact that the Earth's climate has varied between what are actually rather narrow limits is testimony to the efficiency (and delicacy) of the feedback processes. This characteristic permits the balance of heat, momentum and moisture required of the global-scale circulation to be met through the contributions of several processes. Diagnostic studies of the distribution or partitioning of these fluxes among the various modes and components of the system reveal how the climate is maintained in a near-equilibrium state. When such studies are made for a succession of climatic states, they provide important clues on the balances which are characteristic of climatic change. This characteristic compensation is illustrated in the case of the atmospheric heat balance in Figure 4. Here we note that on the average as much energy leaves the top of the atmosphere in the form of long-wave radiation as enters in the form of short-wave solar radiation. Were the absorbing or scattering properties of the atmosphere to change (as, for example, by the addition of large amounts of volcanic dust or CO₂ to the atmosphere), the relative roles of the processes as now observed would also change but in such a way that the overall heat balance was maintained. A similar balance is present at the Earth's surface and within the atmosphere

as a whole. In those cases where observations are lacking or cannot be made, the determination of the possible ways in which the enhancement (or removal) of one process would change the other processes - and hence the climate - is a task for climate models to which we now turn our attention.

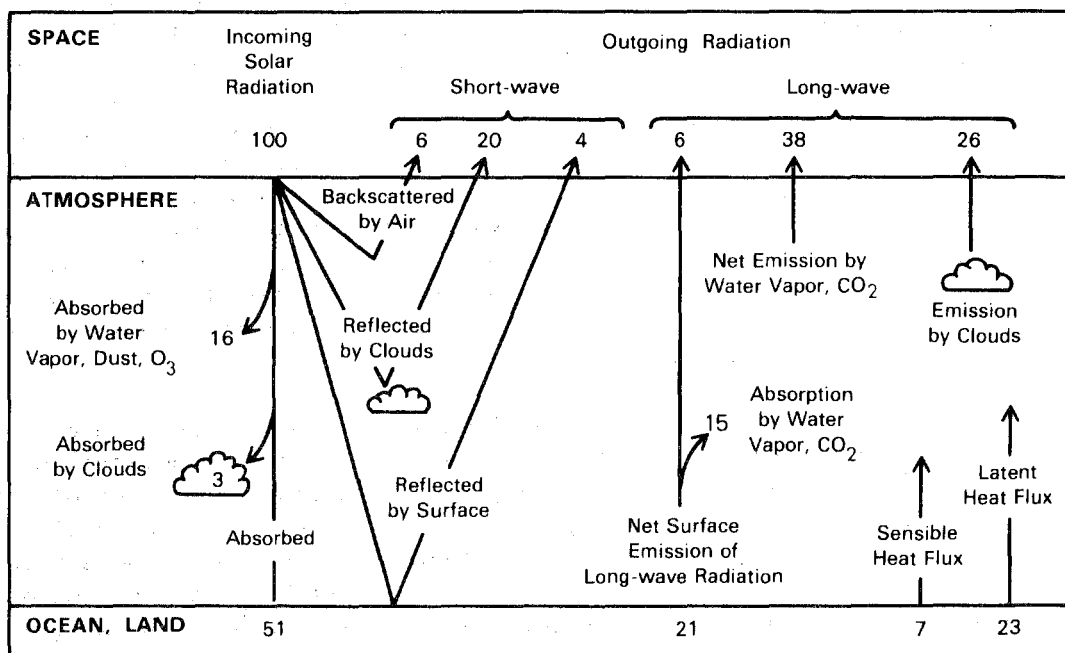


Figure 4. The average radiation and heat balance of the atmosphere-earth system, relative to 100 units of incoming solar radiation. Source: 1

4. Climate models and climate prediction

Our knowledge of the physical basis of climate and of climatic variation is most usefully and comprehensively organized in terms of models based upon the physical laws which govern the climatic system's behaviour. From such models the system's future behaviour or a future climatic state may then in principle be determined. Used in this way, a number of climate models have shown considerable skill in reproducing the present climate of the Earth and that at selected times in the past, but these models have not yet demonstrated skill in the prediction of future climate. It is interesting to note, however, that if man's increasing alteration of the environment results in the introduction of previously unknown influences on the climate, the modeling approach is the only method which can be used to predict the future course of climate.

For the atmosphere, the governing physical laws are expressed by a set of conservation equations which describe the changes of the air's velocity, temperature, pressure and moisture content - the so-called primitive atmospheric equations [6]. In brief, these equations state: that the rate of change of the wind speed is determined by the law of conservation of momentum, in which the effects of the air's horizontal and vertical movement are considered, together with the effects of the Earth's rotation and the forces of pressure, gravity and friction; that the rate of change of the air's temperature is determined by the law of conservation of heat energy, in which the effects of horizontal and vertical motions and the existing temperature distribution are considered, together with the effects of diabatic heating due to radiation, conduction and latent heat release; that the rate of change of the air's pressure is determined by the law of conservation of mass, in which the effects of the horizontal and vertical transports of air are considered; and that the rate of change of the air's moisture content is determined by the law of conservation of water substance, in which the horizontal and vertical transports of water vapour are considered, together with the effects of evaporation, sublimation, condensation and precipitation. A similar set of dynamical equations describes the behaviour of the oceans, while the ice masses, surface lithosphere and biomass are usually represented by more empirical relationships.

These mathematical equations are basically the same as those which are routinely used in numerical weather prediction, except that in their application to climate more attention must be given to the slowly-varying sources and sinks of momentum, heat and moisture which may be relatively unimportant on the time scales of weather. It is therefore crucial in climate models that there be no accumulating errors in the models themselves, since such effects could easily be mistaken for a change of climate over an extended period of time. This requirement applies both to the large-scale processes which can be treated reasonably well by models and to the small-scale processes which cannot be explicitly resolved and which are therefore treated parametrically. Since an important fraction of the vertical fluxes of heat and moisture in the atmosphere is accomplished by smaller-scale motions (such as the turbulent fluxes in the surface boundary layer and the convective fluxes associated with clouds), the parameterization of such processes in terms of the resolved larger-scale behaviour is perhaps the most important feature of a climate model.

Once the necessary boundary conditions are assigned (which in the case of the atmosphere may be taken as the distribution of sea-surface temperature, the surface elevation and albedo, and the solar radiation at the top of the atmosphere), these equations and their associated parameterizations presumably are capable of describing the changes of the larger scales of climate if they can be successfully integrated over the necessary periods of time. Most climate models, however, are so complex that it has been necessary to introduce further simplifications, including the approximations necessary to solve the equations by numerical methods. The resulting mix of physical and numerical representations is also sometimes called a climate model. For these reasons alone, all climate models inevitably distort the true physical processes of the climatic system on some scales, and therefore distort the portrayal of any simulated climate and climatic change.

4.1 Climate model heirarchy

The most complete and detailed climate models are known as general circulation models (or GCMs), of which there are perhaps a dozen significantly different versions for the atmosphere and/or ocean [7]. When used with modern boundary conditions (which includes specification of the sea-surface temperature) the typical atmospheric model is capable of satisfactorily simulating almost all of the large-scale features of the climate as now observed, including the average distribution of the pressure, temperature and wind both near the surface and aloft. The models simulate the observed patterns of those variables associated with small-scale processes such as cloudiness and rainfall with less accuracy, although even here the models' skill is significant [8]. More important, however, is the fact that such models are able to reproduce reasonably well the seasonal changes of climate from summer to winter; this annual display of the atmosphere's (and to a lesser extent the ocean's) sensitivity to the sun's radiation is the best documented climatic change we have, and provides an excellent model calibration. These models have been less successful, however, in reproducing the variance and higher-order statistics of the atmospheric climate other than those imposed by global balance requirements.

Since the atmospheric general circulation models are able to reach climatic time scales only by a step-wise numerical integration during which the behaviour of individual mid-latitude atmospheric cyclones and anticyclones is simulated in some detail, the climatic states and hence any climatic variation derived from them inevitably contain a sampling error due to the presence of such disturbances. Unless an integration is carried out for a relatively long time or unless an ensemble of experimental realizations is available, a climatic variation of physical origin may remain undetected within these essentially statistical fluctuations. The separation of a possibly significant climatic change signal from such essentially unpredictable climatic noise is therefore an important aspect of climate research with such models.

In spite of the power and generality of the GCMs, at least certain aspects of the climate system can be successfully depicted with models of considerably less sophistication. These simplified models are usually based upon a one- or two-dimensional representation of the energy balance or upon a zonally-averaged version of a more complete three-dimensional model [5, 9]. Such statistical-dynamical models do not attempt to simulate the detailed behaviour of synoptic-scale disturbances and are therefore capable of economically simulating long-term climatic states with little or no climatic noise. This ability is achieved, however, at the price of possibly unsatisfactory distortions of critical climatic processes. Climatic changes which involve a trade-off or balance among several processes could therefore be seriously misrepresented by such models. Depending upon how such simplifications are introduced, it is also possible for such models to yield more than one solution for the climate under the same boundary conditions [10, 11]. Whether this lack of uniqueness is also shared by the more comprehensive models has not yet been established, but the mere possibility of such an indeterminacy in the climate suggests an inherent limitation to climate prediction.

4.2 Climate predictability

Even the best model, however, is not yet able to predict the change of the climate over the next decade or century, or even the change from one winter to the next. This is partly the result of errors and inadequacies in the models themselves (not the least of which is their neglect of the coupling between the atmosphere and the ocean), and partly due to an inherent lack of predictability in the atmosphere and oceans themselves. Recent theoretical and numerical studies have shown that the detailed behaviour of the atmosphere probably cannot be predicted by any method for longer than about two weeks' time - a limit, we may note, which current weather forecasts have not yet reached /2/. Beyond this time, our inability to observe and follow every part of the atmosphere in minute detail eventually destroys whatever ability our models may have in predicting the local sequence of the weather over longer time periods. As we have already noted, however, this circumstance does not prevent us from calculating the statistical properties of the atmosphere under conditions such as have occurred in the past or may occur in the future, even though we may not be able to trace the detailed course or time evolution by which a past or future climate evolves. Such a calculation is sometimes called a climatic scenario, and is like taking a "snapshot" of a supposedly equilibrium climate without knowing how or at what rate that particular climate came into being.

4.3 The CO₂-climate problem

Even though the limits of the predictability of climatic change are not yet fully understood, the calculation of future climates can still be made by the scenario method discussed above. Some of the most challenging scenarios that can be produced with climate models are those concerned with the possible climatic effects of man's activities; of these, the problem of the effects of carbon-dioxide in the atmosphere is perhaps the most important. Since the industrial revolution began in earnest in the mid-nineteenth century, man has consumed increasing amounts of coal, oil and natural gas as part of his accelerating industrialization and rising standard of living. Part of the carbon-dioxide which results from this combustion of fossil fuels is taken up by the Earth's surface vegetation, and part is absorbed by the surface waters of the ocean and slowly mixed downward into the deeper water. The rate of CO₂ production, however, has overwhelmed these natural removal processes, and the amount of CO₂ resident in the atmosphere has increased steadily since about 1880 /12/. At the present time the atmosphere contains about 15 per cent more CO₂ than it did only a century ago. The importance for the climate of this seemingly small change lies in the effect CO₂ exerts on the atmosphere's temperature through its strong absorption of the long-wave or infrared radiation emitted by the Earth as part of the planetary radiation balance (see Figure 4). This absorption serves to maintain the temperature in the lower atmosphere at a somewhat higher level than would otherwise be the case. By increasing the amount of CO₂ the atmosphere's temperature tends to rise even further as the greenhouse effect is enhanced.

If the atmospheric CO₂ continues to increase at the nearly exponential rate indicated by recent measurements, it is estimated that its concentration will nearly double its present value sometime in the next century. Should this circumstance occur, preliminary model calculations indicate that the average temperature near the surface will rise by several centigrade degrees. Such a change is sufficient to have a

serious impact on the yields of the world's major agricultural regions and could trigger other, as yet unforeseen, changes of climate. This prospect is made even more serious by the projections that a second doubling of atmospheric CO₂ concentration may occur late in the twenty-first century if present trends continue, in which case the global warming may amount to a climatic catastrophe. Although the slow removal processes of the ocean would eventually come to our rescue, the Earth would enter a period of warmth greater than it has ever experienced which would, moreover, last for several hundred years. If further research confirms this scenario, the CO₂-climate problem appears destined to become the major environmental crisis of the future, and its resolution will be a prime factor in the world's future energy strategy.

5. The need for further research

The need for intensified research on the dynamics of climate is underscored by our ignorance of the possible near-term climatic effects of many other processes, both natural and man-made. In addition to the effects just mentioned, these include the effects of volcanic dust, of chemical contamination of the atmosphere, and of large-scale land clearing, irrigation and urbanization. To answer these questions will require a sustained research effort, including both the collection and analysis of new climatic data and the further development and application of climate models.

In both future diagnostic and modelling research, priority attention should be given to the study of the coupled atmosphere-ocean system /13, 14, 15/. Despite their overall success, most atmospheric models continue to display systematic errors in the simulation of many climatic variables related to this coupling, such as the cloudiness, tropical precipitation and ocean surface heat flux. To reduce these and other shortcomings, further improvements are needed in the models' parameterization of processes on both turbulent and convective scales, especially those processes involving exchanges of heat, momentum and moisture between the atmosphere and tropical oceans. There is also a need for comprehensive intercomparisons of the performance of different climate models, especially with respect to their relative sensitivity to a variety of climate change mechanisms. With such information, the systematic exploration of past, present and possible future climates may be undertaken in a consistent manner and systematic estimates of the climate's impact upon human affairs may then be made. Such long-range programmes are now being considered by various governments and by the World Meteorological Organization itself in the form of the World Climate Programme. The almost incalculable value which an understanding of the physical basis of climate and its changes would have for man's year-to-year agricultural activities /16/ and for his longer-range water supply /17/ and resource management planning, justifies our best efforts toward this goal.

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MODELLING OF CLIMATIC CHANGES

AND

THE PROBLEM OF LONG-RANGE WEATHER FORECASTING

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1. Introduction

When studying climate it is essential to know what changes or fluctuations have occurred in terms of the characteristic time scales that are involved, i.e., thousands, hundreds or tens of years. We are therefore concerned respectively with epoch-long climate, century-long climate or so-called "locally-temporal" climate.

Each of the climates has its own temporal and spatial averaging scales for meteorological characteristics and its own statistical fluctuations and correlations. Thus, for epoch-long climate the century-long changes are statistical fluctuations; for century-long climate the corresponding fluctuations are locally-temporal changes; for locally-temporal climate the statistical fluctuations are annual and seasonal weather changes.

To determine climatic changes in general one has first of all to trace changes of locally-temporal climate, because such knowledge is very important in forecasting climate for individual large regions of the globe and for time intervals comparable to the lifetime of one generation of people. It should be noted that studies of natural climatic changes over periods of tens of years may be provided by the actual data about the processes occurring in the atmosphere and the ocean.

Primary among these processes responsible for climate is the rate at which heat is added to the climatic system and its inhomogeneous distribution over the globe. The ultimate source of heat is of course the sun's radiation. The atmosphere and the ocean respond to this heating by developing winds and currents, which in turn serve to transport heat from regions where it is received in abundance to regions where there is a thermal energy deficit.

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Time scales of internal atmospheric interactions range from seconds to ten days and involve the great variety of motions that develop in the atmosphere from weak wind gusts to intense planetary-scale cyclones. These processes are mainly associated with weather phenomena. As for oceanic processes, their characteristic time scales vary much more significantly, ranging from seconds to thousands of years. Estimates show that poleward heat transports in the atmosphere and the ocean are comparable in value. This means that the world's oceans play an important role in forming climate and its changes.

Due to the complexity of the problems facing us the development of a hydrodynamic model of climate capable of describing atmosphere-ocean interactions is of fundamental importance [1].

Today studies of the effects of persistent sea surface temperature anomalies in the tropics on atmospheric circulation in mid-latitudes, such as those first performed by Bjerknes [2], are of great value to science. Of importance are studies by Wyrski [3] devoted to the effects of anomalies in the trade wind field of the West Pacific on the subsequent persistent anomalous oceanic circulation in the East Pacific, the so-called El Niño. The same is true in the case of research carried out by Namias [4] and Musaeljan [5] devoted to the effects of persistent temperature anomalies in mid-latitudes in the open sea in summer seasons on the atmospheric temperature anomalies of the North American continent and Europe in subsequent autumn seasons.

The known effects of the sea surface temperature anomalies on climatic processes are, possibly, the simplest cases of persistent direct thermal effects of the sea on the atmosphere. Most other effects manifest themselves indirectly as a result of various unstable processes occurring in the atmosphere and the oceans.

Seasonal variations from year to year in the heat added to the atmosphere and the oceans are so significant that one cannot discover or understand the importance of the physical processes responsible for climatic changes, without considering these variations. According to Kurbatkin [6], the atmosphere-ocean interaction generally occurs in irregular cycles. It is characterized by the actions of processes occurring in either the atmosphere or the oceans as well as in either the northern or the southern hemisphere. Moreover, the processes occurring in one medium naturally cause disturbances in the other. At the same time there are active processes tending to re-establish in subsequent seasons some climatically balanced states of their medium. For example, seasonal winter circulations of the atmosphere in mid-latitudes of the northern hemisphere play an active part in the interaction with the oceans, taking away the oceans' heat and generating areas of cool waters in the oceans. In summer in the mid-latitudes and in the subtropics the ocean is warmed up at the expense of the solar radiation and re-establishes its hydrophysical characteristics specific for the summer period, the atmosphere playing a passive role. Summer monsoon atmospheric circulation, though weak, is very important for the general circulation of the atmosphere and the oceans for this part of the year's cycle and also contributes to this.

However, if the areas of cool waters generated by the active winter atmosphere are not warmed up during the following summer, the climate may be more uneven with stronger fluctuations of activity and, consequently, with a less pronounced annual

cycle. For example, the after-effects of oceanic anomalies discovered by Fletcher manifested themselves at very long distances and for about eight following years. One can guess that they could be transmitted by the world's oceans.

It would be possible to formulate a hypothesis which could explain some climate changes associated with the ability of large water masses with anomalous temperature values to migrate persistently in the oceans of the world. Such water masses can reach large depths due to unstable stratification and migrate in the depths of the world's oceans undetected from surface observations. Under unstable conditions and after periods of some months or years these masses can come to the surface and cause significant changes of atmospheric circulation.

Now researchers are facing the problem of climate changes for the near future. Practical aspects of this problem can be solved on the basis of statistical extrapolations according to observed data of the past climate and its fluctuations, and also on the basis of hydrodynamic models taking account of the mechanisms of basic climate-forming factors. If some components of such mechanisms, are not clear, different parameterizations, describing to a certain degree of accuracy the missing components of complicated processes, are introduced into the climate model.

In general, the process of climate anomaly formation can be presented as follows. Over the world's ocean regions there appear cloud formations affecting the solar heat flux to its surface layers. If the cloudiness is less than the climatic norm, it lets more solar radiation through and the surface layer warms up more intensively.

Part of the heat stored by the ocean surface layer goes back to the atmosphere in the form of long-wave radiation and warms it up (see Figure 1). Another part is transported by means of the vertical turbulent exchange to lower layers several hundred metres deep. If the anomalously low cloudiness persists for a long period of time (for a month or a season) a considerable warming of the ocean in this area is observed (of the order of 1 deg C).

The warmed waters are transported by currents to the northern Atlantic and the Pacific oceans as shown in Figure 2. They reach the latitudes where in the ocean surface layer a zone of vertical instability is formed under the influence of the low air temperature. This generates powerful irregular convective motions that release the stored heat from the deep ocean layers to the atmosphere. The most intensive ocean-atmosphere heat exchange in the Atlantic occurs in the area near Iceland, and in the Pacific it is near the Aleutian Islands. In the southern hemisphere it is the area of the Antarctic continent.

The heat of the ocean given up to the atmosphere warms up the air of the given region. Because of the nearness to cold polar regions there arise pronounced temperature contrasts, which lead to formation of intense cyclones that are a form of horizontal release of instability of the air masses. Such cyclones are carried away to the east by the powerful mid-latitude planetary flow, transporting portions of heat to the continents and creating warm zones there. If we consider the velocity of flows in the Atlantic and the Pacific and the time for removal of the active warm body of the surface subtropic waters from the critical northern areas of intensive

heat exchange it appears that this process could take approximately as long as one season. It means that substantial temperature anomalies in the ocean will affect the weather of the continents after several months.

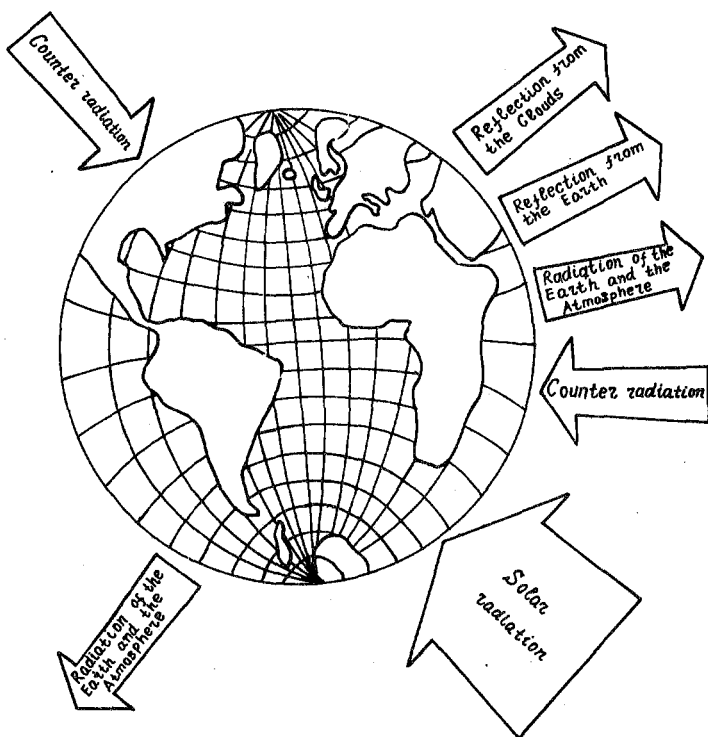


Figure 1.

Schematic of components of radiation balance in the atmosphere

Figure 2.

Mean surface flows in the Atlantic Ocean



In this complicated process of the Sun's radiant energy conversion into kinetic energy of atmospheric motions one can trace numerous direct connexions and feedbacks responsible for climate fluctuations. The nonlinear nature of these connexions is the most important factor for maintaining relative stability of atmospheric processes.

Of course, anomalies of cloudiness are themselves the result of complicated hydrothermodynamic processes, hence the choice of cloudiness as the main component in the regulation of the heat regime of the atmosphere-ocean system is in a sense a matter of condition. Furthermore, connexion of heat flow with cloudiness is rather sophisticated and is not always single-valued in interpretation. Therefore, strictly speaking, in many cases we ought to deal with heat flow anomalies rather than with cloudiness anomalies.

2. Climate models

Before we pass to the discussion of mathematical simulation of the atmosphere and its general circulation, we will recollect the main features of the mechanisms governing atmospheric dynamic processes.

The first feature of the atmospheric (and oceanic) motions is that the hydrodynamic processes in these systems take place on the rotating Earth (see Figure 3). Air masses which would otherwise travel in the opposite direction to the pressure gradient (from the high pressure to the low pressure area) on the rotating Earth, due to the Coriolis force, travel approximately along isobars (lines of equal pressure), rather than across them. Motion of this kind is said to be geostrophic.

The deviation of the air mass motion from these quasibalanced trajectories (isobars) is rather small. But it is this deviation that is responsible for the evolution of the meteorological fields. Therefore the first difficulty in simulating the dynamics of the atmosphere is that in describing the field of flows the factors that affect the dynamics of the atmosphere are rather small and can only be obtained as differences of large values, i.e., the components connected with geostrophic wind.

Second, the annually averaged and approximately uniform pressure at the Earth's surface (at sea level) becomes more and more different from level to level of the troposphere, so that at the higher altitudes the equatorial pressure becomes higher than that at the poles. As a result a pressure gradient appears. Since isobars in this case approximately co-incide with the latitude circles, in the mid-latitudes there arises a planetary geostrophic west wind as shown in Figure 3. It is proportional to the pressure difference, and it gains strength with increasing altitude approximately linearly and reaches its maximum at the tropopause level. This wind is usually called the west-east atmospheric transfer. Its mean in the troposphere is 10 - 15 m/sec. The west-east transfer plays a very important role in the life of the atmospheric processes by transporting the meso-scale (of the order of 1 000 km) disturbances and exerting an essential influence on the transfer of the large-scale planetary perturbations. Such perturbations are deviated westward by inertia and travel against the planetary flow. If one takes into account the fact that the velocity of the west-east transfer changes depending on the energy state

of the atmosphere, and that cyclonic- and anticyclonic-type perturbations constantly evolve, then it becomes clear how extremely difficult it is to determine the location of a perturbation in any given area.

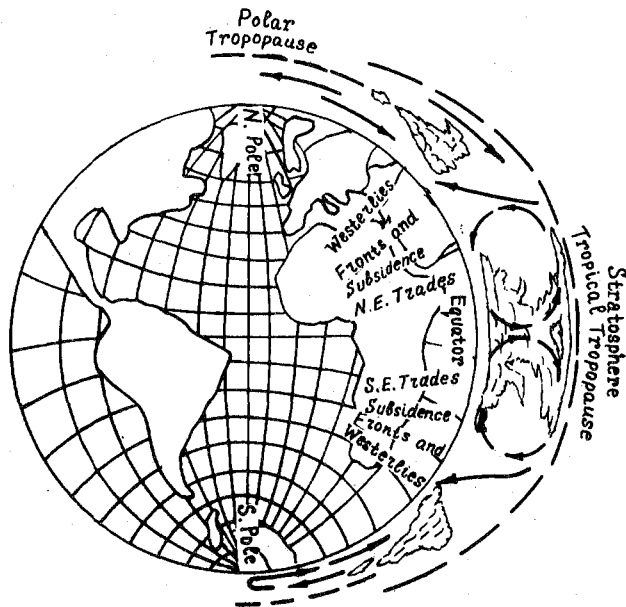


Figure 3.

Schematic of mean meridional circulations in the troposphere

The third feature of the atmosphere is the pronounced turbulent character of the processes occurring in it. Turbulent vortices of different scales (from cyclones to microscopic eddies) continuously arise in the atmosphere while the stability of basic motions is lost. After separating from the main flow, a turbulent vortex becomes the carrier of definite stores of kinetic and internal energy. Having an essential freedom to travel within the flow, due to its newly-gained hydrodynamic stability, such a vortex migrates in the system while interacting with the basic flow and other vortex formations. As a result of complicated interactions the vortex loses its stability and disintegrates into smaller vortex formations that are also steady for a short time. This process continues until the size of vortices becomes so small that molecular viscosity begins to act on it. Under the effect of viscosity the vortex dissipates, and its kinetic energy adds to the warming of the atmosphere. Thus, we deal here with the turbulent cascade of vortices of constantly decreasing size.

However, parallel to such natural processes of turbulent energy exchange, another important mechanism of the turbulence evolution acts in the atmosphere. The latter is due to the enlargement of the scale of quasi-two-dimensional vortices, which are sometimes said to be macro-turbulent fluctuations. Such a process begins with vortices of a definite size. This process arises in the medium where a vortex ensemble has been formed. Hydrodynamically interacting, under favourable conditions, small vortices transform themselves into a larger-scale steady vortex. This process may go on after the appearance of larger vortex formations. Thus, a cascade of ever larger turbulent fluctuations takes place.

Actual atmospheric motions are more complicated, because in the background of the mean current there arise simultaneous turbulent exchanges which involve both chains of the cascade process. It is of great importance to understand the role of the turbulence exchange mechanism for the atmosphere, because it is the turbulence that causes the atmosphere-ocean and the atmosphere-ground interactions. So a mathematical description of turbulent exchange and the correct incorporation of this mechanism into hydrothermodynamic equations are of great importance for developing climate prediction methods.

Studies of Kolmogorov, Obukhov, Taylor, Batchelor, Monin and others played important roles in developing turbulence theory with respect to atmospheric processes, especially for the conditions of homogeneous turbulence. Based on these studies different parameterizations of the turbulent exchange in atmospheric boundary layers were determined, the latter being the region of the most intensive vertical energy exchange.

The fourth feature is related to the mechanism maintaining the thermal regime of the atmosphere. Though there is only one source of heat in the atmosphere, the Sun, there are several ways to convert the solar radiation into thermal energy. One of them has already been mentioned when considering the dissipation of the kinetic energy of turbulent fluctuations. The energy of the direct solar radiation absorbed by the surface layer of the world's oceans and the continents plays a more important role in creating the thermal regime in the atmosphere. The amount of radiation thus absorbed depends mainly on the cloudiness, as well as the amount of water vapour, the albedo of the underlying surface and many other factors. Clouds reflect solar radiation almost completely, and the world's oceans (when clear of clouds) almost completely absorb it. The amount of the absorbed solar radiation depends essentially on the character of the underlying surface.

We have not yet considered such important factors as the ozone layer in the stratosphere and carbon dioxide gas and aerosols in the troposphere. Though we have data on the mean climatic state of the atmosphere, in reality the deviation of these values from the climatic norm proves to be so important that it may have a fundamental influence on the establishment of meteorological states. So, in spite of the fact that the mechanism of the short-wave radiation transfer is well studied, we do not possess sufficient information on the actual state of the ozone layer, the atmospheric aerosol density, etc., which, if not considered, lead to bad mistakes in the forecast of climate changes.

Another aspect of this complicated problem is the long-wave radiation transfer. The ocean and continent surfaces, warmed by the Sun, emit long-wave radiation which is partially absorbed by water vapour, ozone and carbon dioxide, thus heating the atmosphere, and partially escapes to space. If there is a cloud in the way of the long-wave radiation it is absorbed by the lower part of the cloud, thereby warming it. The warmed part of the cloud begins to re-emit radiation to the Earth. A so-called "greenhouse effect" is created. These are the main radiational factors that must be considered in developing hydrodynamical models of the atmospheric general circulation (see Figure 1).

In the last 20 years, beginning with Phillips [7], we have witnessed an explosive development of ideas and methods of numerical modelling of atmospheric processes. In the referenced paper it is shown that, in spite of essential simplifications made in the model, one can obtain solutions with a qualitatively correct description of the fundamental characteristics of the atmospheric circulation. Since then we have gained an understanding of what physical processes are to be described in the first place so as to simulate more or less correctly the basic characteristics of the atmosphere and to construct for this purpose the necessary hierarchy of models.

This hierarchy of models can be classified according to the description of the system's thermodynamical characteristics. The simplest models (i.e., those of "zero" dimension) are models describing the atmospheric temperature based on thermodynamical equations of energy balance (Budyko [8], Sellers [9] and others). Simple as they are, zero dimension models can be used in paleoclimatic studies. More sophisticated one-dimensional models, the so-called convectively adjusted radiative-balance models, allow introduction of the vertical distribution of atmospheric characteristics (Manabe, Wetherald and others [10]) and, in our opinion, they provide the possibility of simulating specific features of century-long climate. In this respect, fundamental contributions to the theory of climate have been made by Smagorinsky and Manabe [11, 12], Mintz and Arakawa [13, 14], Leith [15], Kasahara and Washington [16] in their works on mathematical simulation of the atmospheric general circulation as well as by Charney [17], Thompson [18], Lorenz [19], Phillips [7], Gates [20], Monin and Obukhov [21], Kurbatkin [6, 22, 23], Kondratiev [24], and many others who studied the physics of large-scale circulations. As for problems of description of the ocean thermodynamics and the atmosphere-ocean interaction processes, they have only quite recently become the focus of attention of researchers.

Analyses of atmospheric general circulation hydrodynamic models are being presented in papers by Mason and Gates at this Conference. Therefore we will discuss here only some problematic aspects that require attention and further research.

There is first of all the problem of cloudiness. It is well-known that cloudiness is the main regulator of short- and long-wave radiation fluxes. Therefore the efforts of researchers who develop radiation models are basically aimed at a creation of radiation models of clouds of different types. It should be noted that all existing atmospheric general circulation models rather poorly describe cloudiness fields, because they calculate only the presence or absence of clouds, whereas all other cloud characteristics are assumed to be climatic. If one takes into account the important thermal regulation role of cloudiness in problems under study it becomes clear that the solution of such problems presents an urgent task.

Among other tasks requiring the close attention of researchers let us mention the parameterization of the convective processes, especially those which are responsible for development of tropical disturbances. Results obtained in this difficult field are encouraging, though they require further thorough study.

Much attention is to be paid to parameterization of processes taking place in boundary layers, regulating interaction of the atmosphere with the oceans and with the continents; and also to effects of orographic inhomogeneities at the Earth's surface as well as to the problem of the "upper" boundary condition in the atmosphere.

In spite of the fact that there are still many unsolved problems in the field of atmospheric circulation modelling it is safe to say that meteorologists have currently achieved a very high level in their understanding of atmospheric processes and in their description of them.

Due to the progress made in the development of atmospheric general circulation models and the numerical methods for their solution by the most advanced electronic computers, we have now at our disposal a considerable body of information about our planet's climate. That now gives us an idea of how exactly a mathematical description can be given of the atmospheric as a whole and the different components its circulation.

Most mathematical models currently in use are based on actual data for the ocean, whose basic characteristics are presumed to be known. This leads to a considerable simplification of the model of the atmospheric processes and speeds up the approach to a solution to climate modelling.

General ideas of the ocean dynamics simulation problems were influenced by the studies of Stommel [25], Munk [26], Sarkisian [27], Lineikin [28], Welander [29], Robinson [30] and others (see Figure 2, for example). A number of numerical models of the oceanic general circulation have been currently developed on the basis of the equations of heat or density transport, momentum and salinity transport (Manabe and Bryan [12], Sarkisian [27], Kochergin [31] and others).

Information about atmospheric processes in such ocean circulation models is generally borrowed from climatic observations. Thus, the problem of the oceanic dynamics is greatly simplified. Currently, we have reached a level in mathematical modelling of the world's ocean which allows us to study not only the most important characteristics of the planetary oceanic circulation, but also its details. Because of a wide spectrum of wave disturbances characteristic of the ocean the problem of climate modelling in the ocean is much more complex, as it involves huge demands for computer time. This is the result of the slow physical adjustments of climate in the ocean, which occurs, in fact, over hundreds of years. It should be noted that, given the hydrophysical characteristics at the ocean's surface, climate in the atmosphere is established over several years or less. In this way we have now two lines of research concerned with modelling of climate, i.e. models of climate of the atmosphere and models of climate of the oceans.

Our present state of knowledge of the climates of the atmosphere and the oceans has allowed us to approach a joint solution of the atmosphere and ocean general circulation problem. This is an exceedingly difficult problem, as it concerns a large set of physical mechanisms, a variety of scales of hydrothermodynamical processes occurring in the atmosphere and the ocean, and a large body of information to be used in numerical modelling. Its solution attracts the particular attention of meteorologists.

3. Estimation of climatic changes and the problem of sensitivity

At present there are two main concepts of the problem of climatic changes. The first one presupposes the possibility of substantial changes of the century-long

and locally-temporal climates due to weak stability of atmospheric processes. Under these conditions even with comparatively small variations of the parameters, climatic changes may prove to be very substantial. Quantitative forecasts of possible climatic changes in this case require very precise models that are only now being formulated. Hence, it is a matter of the possible realization of one or another qualitative picture of climatic change. This presents researchers with problems of studying the physical mechanisms that determine climate, and of designing mathematical models of the climatic system, rather than solving them.

The second approach is based on the hypothesis of relative stability of climate with respect to variations in parameters of the climatic system. This approach presupposes as possible quantitative estimations of climatic changes based on the theory of perturbations and allows one to make an attempt to forecast climatic trends for the next few years using information about variations of certain parameters.

The above approaches to the study of climate variations can be considered from the standpoint of the theory of sensitivity of mathematical climatic models to modification in the input parameters. Sensitivity studies of a climatic system should be directed towards investigations of its behaviour in space and time, depending on input parameters. Sensitivity is a measure of the degree of the system's stability with respect to variations of external stimuli, and also to changes of the internal structure of the models.

It is necessary to devise special mathematical techniques to study variations of climate under the influence of human factors and a model's sensitivity to small perturbations of the basic parameters that determine the state and the behaviour of the climatic system. Methods of numerical simulation and perturbation theory with the use of the so-called "conjugate equations" of the atmosphere and general oceanic circulation constitute the basis of this approach.

Sensitivity of climate models is characterized by influence functions for the solution, depending on the choice of parameters and the domain of solution definition. The use of sensitivity functions makes it possible:

- (a) to carry out qualitative analysis of models with the aim of finding out the relative role played by various physical factors, and of planning numerical experiments,
- (b) to formulate new problems of analysis and forecast of climate,
- (c) to develop efficient and stable algorithms for estimation of the effect of small variations of input parameters on the modelled processes,
- (d) to formulate and solve a number of inverse problems of identification of model parameters,
- (e) to evaluate the spatial and time scales of the effect of perturbation of parameters.

A number of sensitivity studies of the climate system with respect to parameter variations were performed with few-parameter climate models by Budyko /8/, Mitchell /32/, Sellers /9/, Lindzen and Farrel /33/ and others and with atmospheric general circulation models by Mintz and Arakawa /13/, Manabe and Wetherald /39/, Chervin, Gates and Schneider /20/ and others. Among these experiments special mention should be made of the experiment by Manabe and Wetherald on the effect of changes of the solar constant and carbon dioxide concentration on climate. We do not intend to give a complete review of all the studies here. They are described in special publications and in papers by Mason and Gates at this Conference. We will present general principles of numerical modelling in sensitivity studies.

The authors of the above-cited papers have generally used a common method of direct modelling. The essence of the method is as follows. A model climate problem is solved twice, first with unperturbed and then with perturbed sets of input parameters. This results in two solutions, and the desired variation is calculated as a difference between these two solutions. In numerical experiments the above direct modelling method is the simplest and the one most universally used. However, if the input parameter change is large and the mathematical model together with its computer algorithm are complicated enough, it is necessary to perform a large set of numerical experiments in order to estimate by this method the effect of variations of individual output parameters /20/. That is why a detailed study of sensitivity presents a problem for even the most powerful computers.

One of the difficulties of using the direct modelling method is the necessity to calculate solution variations by subtraction. In fact, solutions are only found approximately, and therefore for small perturbations of parameters the desired variation is obtained as a small difference between two large numbers, each with a certain error, and this can in turn result in considerable error in the result. Therefore it is only reasonable to use the direct modelling method when there are large variations of solutions.

In many cases, however, in order to estimate changes of climate it appears possible to use a direct relation between variations of input data and climatic characteristics. This relation is realized through sensitivity functions and perturbation theory. If the unperturbed values of input data are assumed to describe a climatic state of the fields under study, perturbation theory formulas allow us to obtain practically estimates of small variations of the most important climatic functions with no need to solve basic and conjugate equations many times.

It should be emphasized that it is reasonable to apply perturbation theory formulas when the necessary information is taken from the solution of a mathematical model of climate which incorporates the basic climate-forming sources. The latter are calculated diagnostically by means of the actual meteorological and hydrophysical data about the current state of the climate with the use of hydrothermodynamic equations. And this constitutes, we believe, the most important point concerning the theory of perturbation in relation to the estimation of climatic changes.

4. Long-range weather forecasting and climate

The problem of weather forecasting up to two weeks in advance has been studied fairly thoroughly. The main determining factors here are the initial hydrothermodynamic fields in the atmosphere and the thermal state of land and oceans. Of great importance to the development of hydrodynamic long-range forecasting methods was a paper by Blinova [35] published in 1943, where an attempt was made to formulate a problem of long-range forecasting for a barotropic atmosphere, using a linearized vorticity equation. Analysis of the vorticity equation helped define spectra of wave motions in the atmosphere and construct the first hydrodynamic model of climate.

Essential to forming the modern conceptions of long-range forecasting methods were studies by the American meteorologists Smagorinsky, Leith, Mintz and Lorenz devoted to modelling of the general circulation of the atmosphere. Though these studies were not directly concerned with weather forecasting, they allowed some important conclusions to be drawn about predictability of meteorological characteristics, fluctuations of the atmospheric system, relaxation times of periodic processes in the atmosphere, etc. However, attempts to use these equations for forecasting according to the actual initial fields has led to the pessimistic conclusion that the predictability span of processes by these schemes does not exceed two weeks. After verifying this fact many times it has been concluded that detailed weather forecasting for more than two weeks in advance is in general hardly possible.

Further investigations by meteorologists showed that other formulations of the problem dealing with hydrodynamical forecasting of the anomalies of some meteorological characteristics, averaged over large space and time intervals, were possible for a period up to a season (Marchuk [36], Adem [37]). The mathematical theory of the approach, based on the use of conjugate hydrodynamic equations and on a specially constructed theory of perturbations, was developed at the Computing Centre of the Siberian Branch of the U.S.S.R. Academy of Sciences. The subject of these studies is long-range forecasting of monthly mean temperature anomalies averaged over large regions of the Earth and ranging from one month to a season. The aim of such a forecast is to determine the sign of the mean temperature anomaly. The thermal behaviour of the land and the hydrothermodynamics of the oceans become the main determining factors of long-range forecasting.

Indeed, in a number of cases strong warming of continents by direct solar radiation and their subsequent cooling result in considerable temperature contrasts and changes of the dynamics of atmospheric processes, giving rise to remarkable weather anomalies. However, as a rule, these two factors do not act longer than two weeks. Thus, the problem of investigation of atmospheric-continental interaction is closely connected with the forecast up to a month in advance. That is why the role of oceans increases as the forecasting range becomes longer, because they possess high thermal and mechanical inertia, whereas the atmosphere has low inertia. It seems that the most important initial condition of long-range forecasting is the temperature field in the active layer of the world's oceans. As to the initial state of the atmosphere, its influence on processes on such a time scale is usually insignificant.

As mentioned above, the most important mechanism responsible for the development of weather anomalies against the background of seasonal climatic behaviour of the atmosphere is planetary cloudiness, which creates conditions for non-uniform warming of continents and the world's oceans. Non-uniformly warmed regions of the continents and the oceans change the hydrodynamic course of atmospheric processes and cause deviations of weather from the climatic norm.

The algorithm of long-range forecasting of the mean temperature anomaly of a region, based on integration of conjugate equations of atmospheric and oceanic hydrothermodynamics, makes it possible to define some of the above-mentioned asynchronous relations. Solution of the conjugate problem is space and time function of influence of the input meteorological data with respect to temperature anomalies being predicted (Marchuk 38).

Analysis of the results of numerical experiments with conjugate equations of atmospheric and oceanic hydrothermodynamics has revealed that in the world's oceans there exist areas that exert the most determining influence upon large-scale atmospheric processes developing above the continents. These areas determine background characteristics of climate and weather.

Thus, for example, it has been established that the state of the Atlantic Ocean is of great importance to Europe and Eurasia. In autumn and winter the zone of maximum influence on climate spreads all over the region of the origin of the Gulf Stream (the Caribbean Sea), and in spring and summer this zone shifts to Iceland and spreads northwards.

The state of the Pacific Ocean plays an important role in determining the climate of the North American continent. Thus, in autumn and winter the zone of maximum influence spreads all over the region of the origin of Kuro-Shio; and in spring and summer it shifts to the region of the Aleutian Islands and the regions near the pole. Similar zones of influence can be found in other parts of the world's oceans and in other large regions of the Earth.

In contrast to the problem of prediction of climatic changes, information on the current state of the atmosphere and oceans rather than climatic information is now used to solve conjugate equations. Therefore, for any meteorological situation in the atmosphere, and for any hydrophysical situation in the oceans, it is necessary to calculate its own influence functions characterizing the contribution of other processes for lesser or greater periods of time.

5. An illustrative example

As an example, let us consider a three-dimensional comparatively simple model of thermal interaction of the atmosphere with the active layer of the world's ocean and land. As a prognostic equation we consider only an equation of heat transport, that includes advective and turbulent terms in the atmosphere and oceans and an equation of heat conductivity in the soil. A radiative balance equation is considered at the Earth's surface.

Let us present results of two experiments of calculation of influence functions for mean November surface temperature anomalies of the European territory of the Soviet Union (Experiment 1) and the U.S.A. (Experiment 2), where we used monthly mean climatic data on the wind velocities in the atmosphere and the boundaries of ice and snow covers at the Earth's surface. The Antarctic continent and the Arctic Ocean (except for the Barents and Kara Seas included in the model) were assumed to be covered with ice. The velocity field of oceanic currents was borrowed from the model of the world's ocean circulation. The figures show isolines of monthly mean values of influence functions at the Earth's surface. Time intervals of solutions in Experiments 1 and 2 are respectively 12 and 6 months. The numbers of months increase in the direction of integration of the conjugate problem. Isolines of the influence function (Experiment 1) for months number 1, 2, 5, 6, 9 and 12 are shown in Figures 4, 5 and 6. In this experiment the source of disturbances acts during the month of November (Figure 4a). Note that the direction of propagation of "disturbances" in the conjugate problem is directly inverse to actual velocity direction. When traveling over the Atlantic Ocean surface (Figure 4b) the disturbances penetrate into its upper layer. The magnitude of disturbances, which have entered the ocean, depends on the direction of the wind field in the atmosphere, i.e., whether the centre of the "cloud" of disturbances, containing maximum values of the conjugate function, or only the edge of the "cloud", will pass over the zone of the intense turbulent exchange (the water basin of Iceland). In the upper oceanic layer "disturbances" move opposite to the Gulf Stream. In Experiment 1 they reach the tropical zone of the Atlantic Ocean (Figure 5a) by the middle of the fifth month from the beginning of calculation, thereafter, during three months, maximum values of the function at the Earth's surface are in the tropics of the Atlantic Ocean (Figures 5b and 6a). From approximately the ninth month of the beginning of calculation (Figure 6a) one observes attenuation of disturbances in the Atlantic tropics and strong smoothing of the field and its dissipation (Figure 6b). That is why it is reasonable to carry out calculation of conjugate problems for no longer period than 9 to 11 months, because later the conjugate function becomes very smoothed and in fact it carries no useful information.

Figures 7 and 8 show isolines of the influence function which is a solution of the conjugate problem (Experiment 2) for months number 1, 2, 5 and 6. When passing over the Pacific Ocean in mid-latitudes (Figure 7b), "disturbances" penetrate into its upper layer, inside of which they move against the Kuro-Shio Current. In approximately five months from the beginning of calculation they reach the tropics of the Pacific and from that time on one observes maximum values of the field (Figure 8a). Figure 8 shows marked intensity of the conjugate function also in the northern part of the Indian Ocean. So, of great importance to the mean November temperature of the European territory of the Soviet Union are radiative processes, that take place in the tropics of the Atlantic Ocean and in high latitudes of the northern hemisphere. As to the mean temperature of the U.S.A., of great importance are radiative processes, occurring in the tropics of the Pacific Ocean and in the northern part of the Indian Ocean.

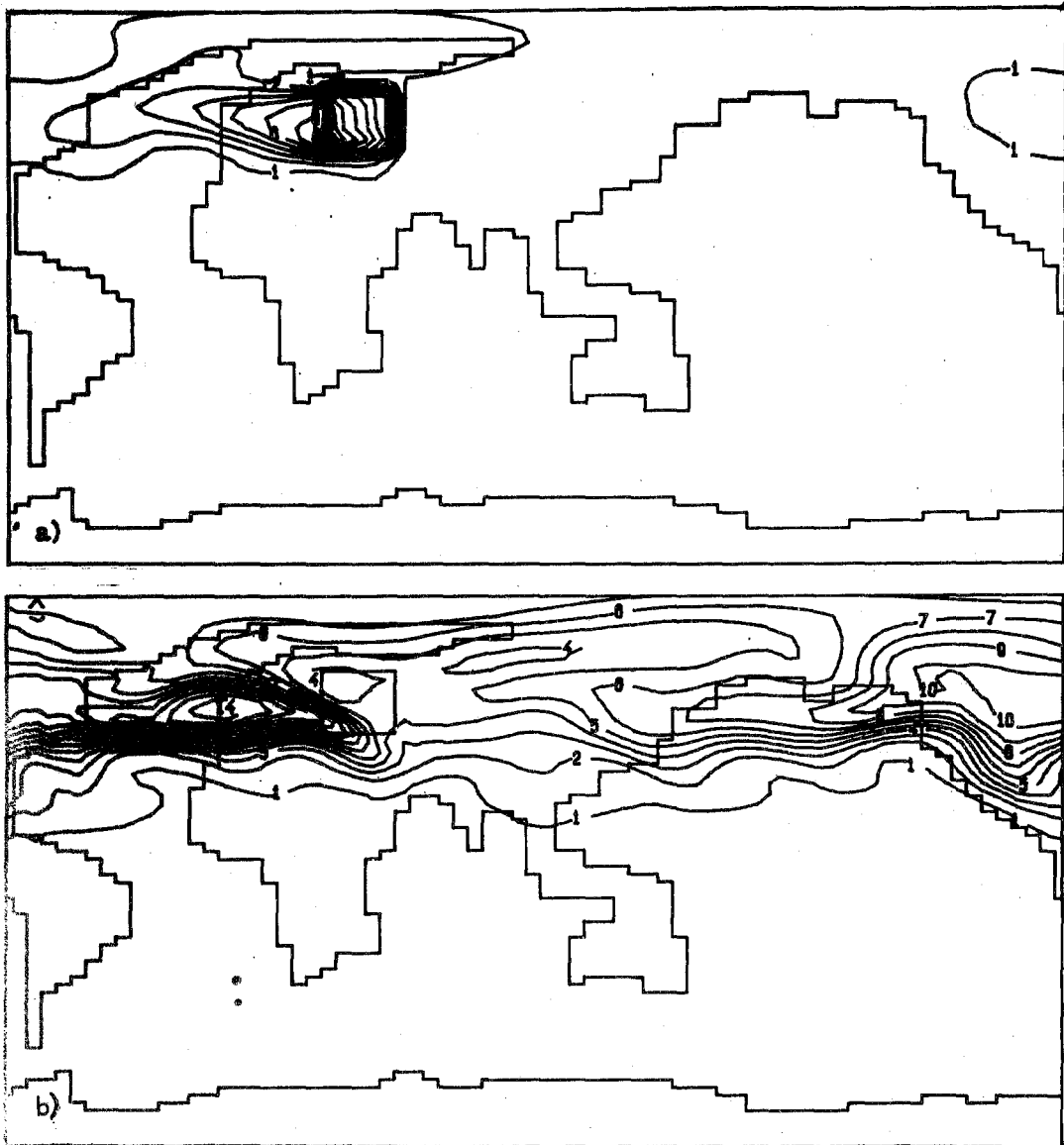


Figure 4. Isolines of monthly mean values of solution of the conjugate problem at the Earth's surface for forecast of mean November temperature anomalies in the territory of the Soviet Union (ETS)
a) 1st month from the beginning of calculation
b) 2nd month from the beginning of calculation.

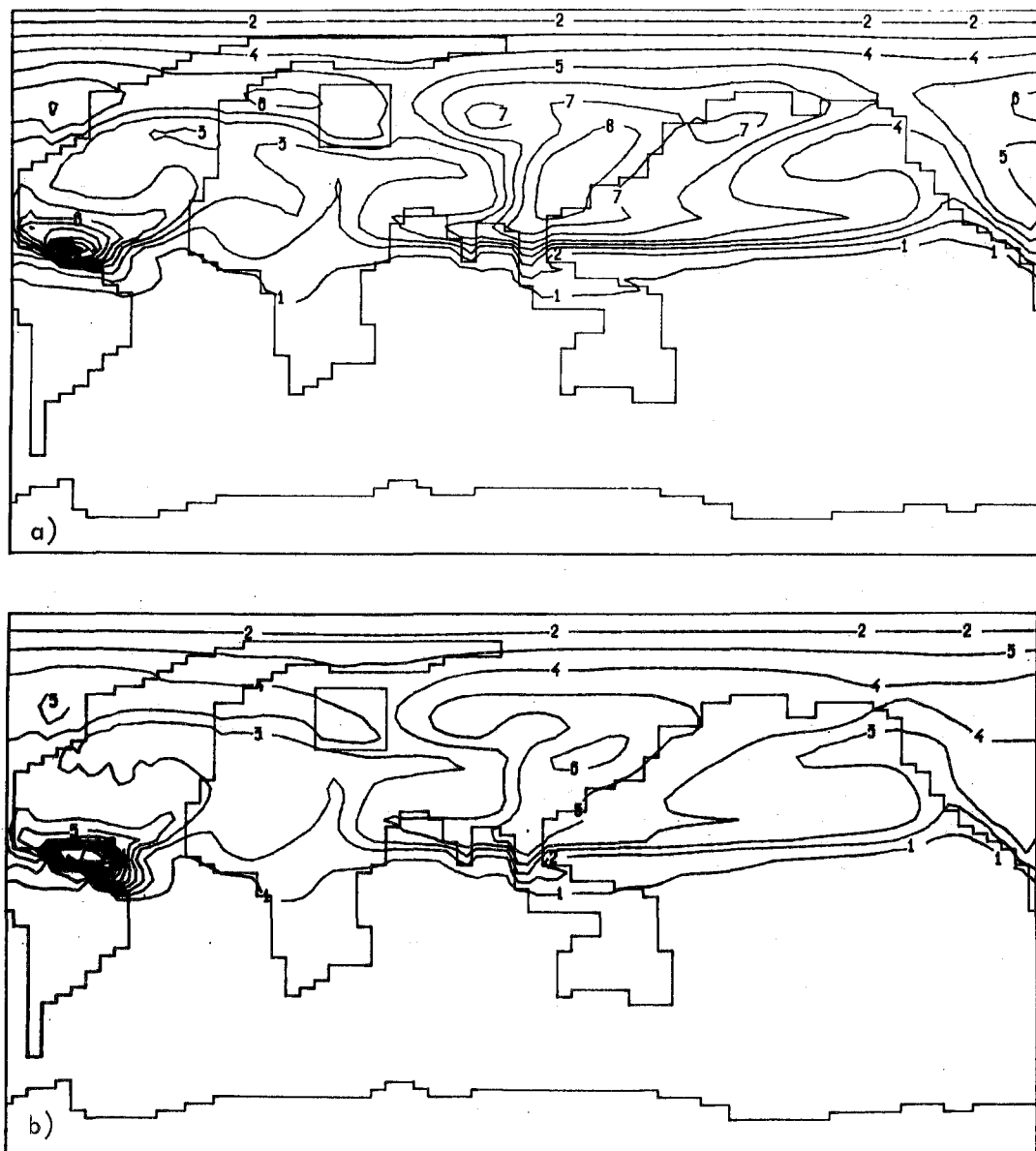


Figure 5. Isolines of monthly mean values of solution of the conjugate problem at the Earth's surface for forecast of mean November temperature anomalies in the territory of the Soviet Union (ETS)
a) 5th month from the beginning of calculation
b) 6th month from the beginning of calculation.

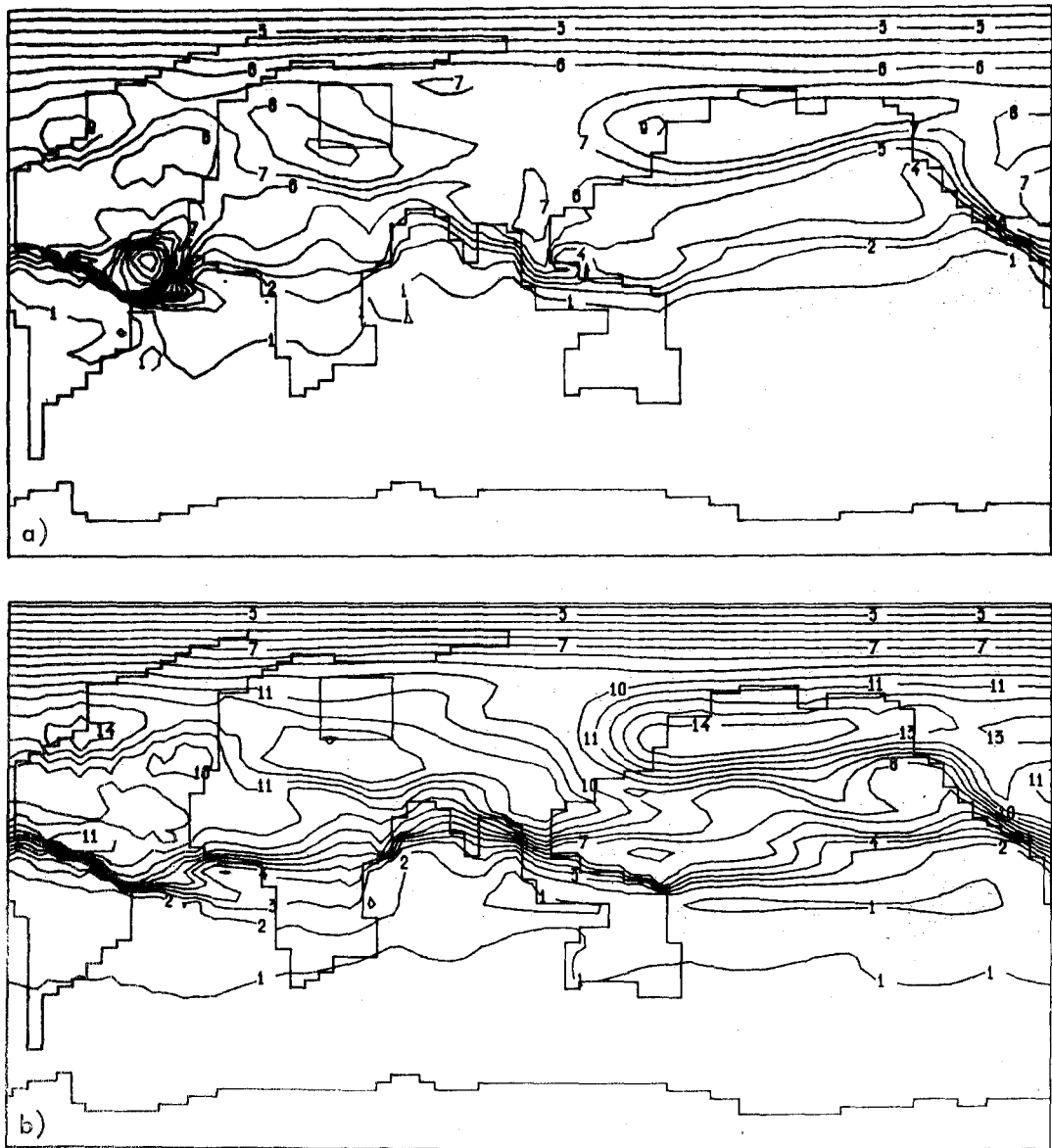


Figure 6. Isolines of monthly mean values of solution of the conjugate problem at the Earth's surface for forecast of mean November temperature anomalies in the territory of the Soviet Union (ETS)
a) 9th month from the beginning of calculation
b) 12th month from the beginning of calculation.

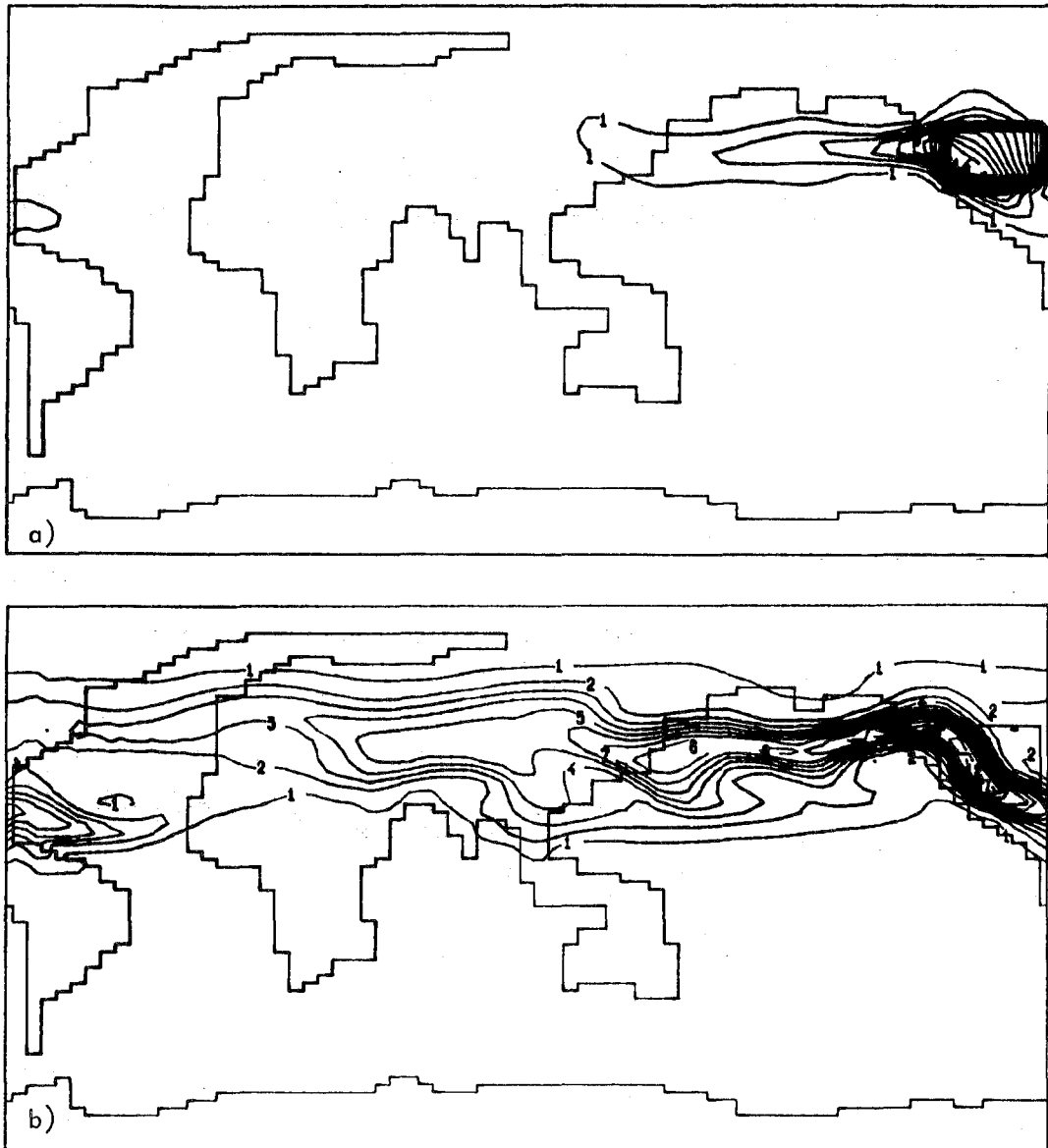


Figure 7. Isolines of monthly mean values of solution of the conjugate problem at the Earth's surface for forecast of mean November temperature anomalies in the territory of U.S.A.
a) 1st month from the beginning of calculation
b) 2nd month from the beginning of calculation.

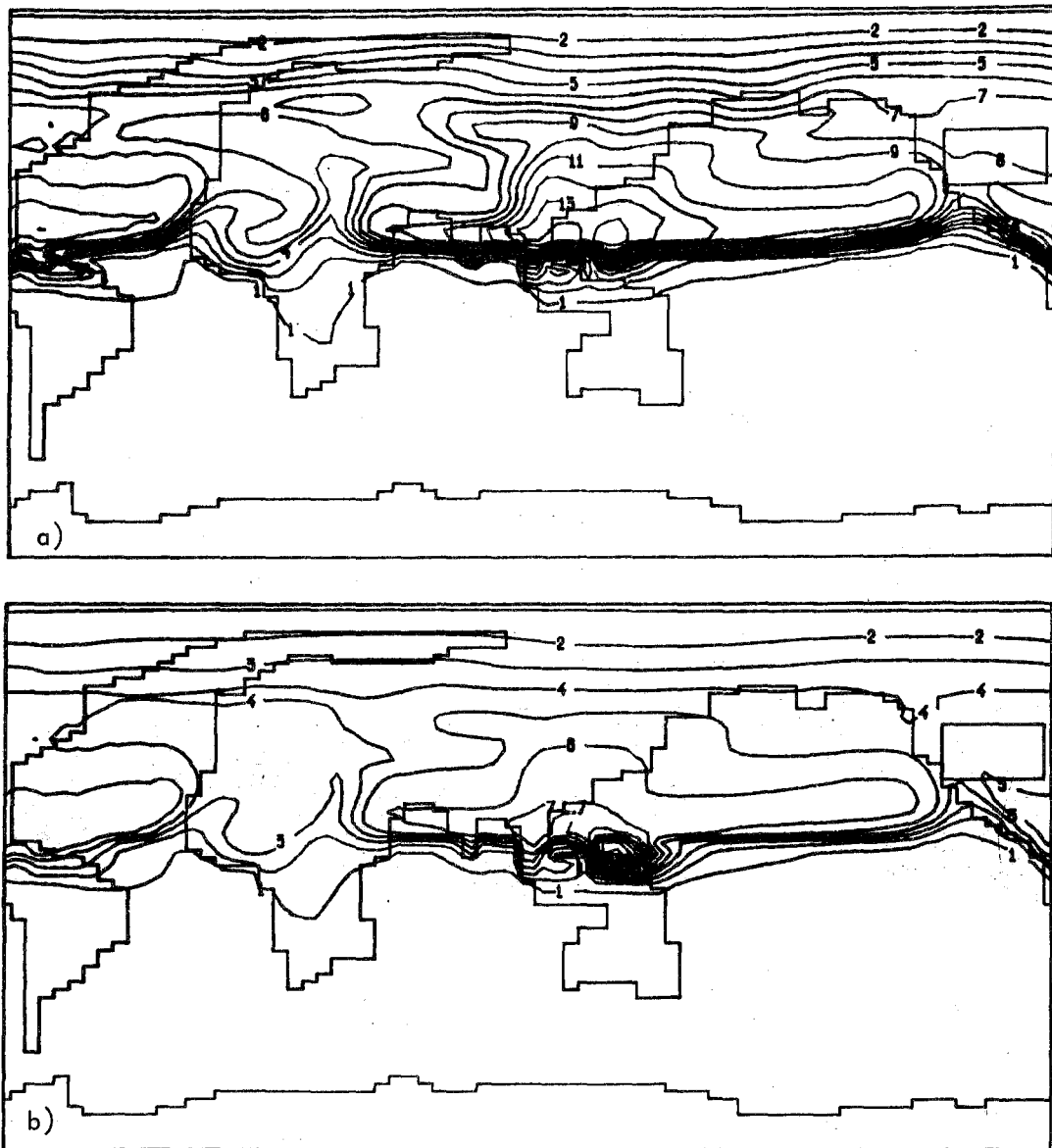


Figure 8. Isolines of monthly mean values of solution of the conjugate problem at the Earth's surface for forecast of mean November temperature anomalies in the territory of U.S.A.

- a) 5th month from the beginning of calculation
- b) 6th month from the beginning of calculation.

6. Conclusion

The purposes of long-range forecasting impose special requirements for hydrometeorological information. Briefly, these requirements are considerably different from those for short-range weather forecasting, because, along with meteorological information they presuppose availability of data on the thermal and hydrothermal state of the ocean, the thermal behaviour of land, boundaries of ice and snow cover, cloudiness and so forth. Without such information long-range weather forecasting, even in its simplest form when only the sign of the temperature anomaly of the region is the functional, proves to be practically impossible.

To a still greater extent it applies to an estimation of climatic changes, which are closely connected with long-range developments usually caused by large-scale hydrothermodynamic transformations, occurring in the world's oceans.

Under these conditions the establishment of a service of hydrophysical data on the state of the world's ocean, based on all-embracing studies, using information from satellites of various kinds, automatic buoys, ships and aircraft is a problem of paramount importance. Of special significance for these purposes at this stage is the Global Atmospheric Research Programme.

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CLIMATE MONITORING AND CLIMATIC DATA COLLECTION
SERVICES FOR DETERMINING CLIMATIC CHANGES AND VARIATIONS

Monitoring Data Relevant to Climate

Ju. A. Izrael*

1. Introduction

The establishment of climate monitoring and climatic data collection services is essential for the study of climate and its potential changes and variations, for the application of climatological information to the development of national economies and for making the most favourable use of the interactions between mankind and nature. The World Meteorological Organization and a large number of national Meteorological Services have over many years collected data on climate and encouraged the utilization of such data in human activities. The Executive Committee of the World Meteorological Organization (WMO) considered climate monitoring and climatic data services as the first objective of the World Climate Programme [1].

Monitoring the environment is understood as a comprehensive programme aimed at the observations of the state of the environment as a whole. However, monitoring is often understood as an observing system which serves the purpose of identification of changes of the state of the biosphere caused by anthropogenic factors [2]. According to this definition, climate monitoring includes observations, assessment and forecast of anthropogenic changes and investigations into the sources and reasons for such changes.

In order to understand climatic change and variation, the data required concern not merely the state of the atmosphere but the state of the whole climatic system consisting of atmosphere-ocean-cryosphere-land surface-biota. A comprehensive study of natural climatic variability should be undertaken to show separately the anthropogenic changes and the variations of climate.

2. Monitoring and climatic data collection services in research and in the solution of applied problems

The reliable description and assessment of the modern climate and forecasts of its potential changes and variations require comprehensive data to allow a detailed analysis of the state of the environment and the development of climate models [3].

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The solution of numerous practical problems in agriculture, energy production, construction and other fields of man's economic activity requires a great deal of information on climate. For such purposes climatic data collection services appear essential and should probably have the highest priority.

A large body of information concerning the individual characteristics of the biosphere's elements and the processes governing climatic variability is necessary for improving our understanding of climatic change and variation.

Of first importance is the study of natural space-time climatic variability on different scales, taking into account the inertial nature of the climatic systems. Forecasts of seasonal and yearly climatic variations require the establishment of a specific global observing system that would be non-uniform with respect to space and time. The identification of the zones of the globe, including the oceans, responsible for climatic variations is of much importance for the establishment of such a system. For instance, as Academician Marchuk has shown 4, weather in a number of regions of the northern hemisphere depends to a great extent on the state of the ocean and its interaction with the atmosphere in the equatorial part of the Atlantic Ocean and in some parts of the Pacific.

The establishment of a data collection system dealing with past climates may also be referred to as monitoring. Such a project requires the development of a system for collection and investigation of fossils and other indirect data (remnants of dead trees, bottom sediments, moraine deposits; analysis of ice columns, pollen analysis, etc.) relevant to the probable climatic variations and changes occurring during past centuries, millennia and even more remote periods of time. The analysis of such data would improve our knowledge of the effects of the climatic system's changes on past climates.

The problem of potential anthropogenic changes of the climate requires knowledge and understanding of the effects of changes of the underlying surface on climate (e.g. changes due to construction of large hydrotechnical structures, changes of forested areas and other activities), the study of anthropogenic changes in the composition and optical properties of the atmosphere (e.g. changes due to the emission of aerosols and different gaseous pollutants, as well as the effects of the emitted heat). The assessment of global atmospheric pollution and its impact on climate is acknowledged by UNEP as one of the main purposes of the Global Environment Monitoring System (GEMS) 5.

Natural and anthropogenic changes of climate can, in their turn, influence the state of the biosphere, causing various ecological changes, and have a pronounced effect on man's economic activities, notably in relation to water resources, agriculture, health of various plant and animal populations and, in the final analysis, human health and welfare.

The above studies are of great practical importance and call for the establishment of a special observing system. The study of impacts on ecological systems in different regions will probably require complex observations in zones untouched by local anthropogenic activity, i.e. in biosphere reserves.

3. Basic problems and purposes

Climate monitoring and climatic data collection are required for solving an extremely wide range of complex problems and, in consequence, the objectives may be formulated as follows:-

- (a) Measurements of climatic parameters, determination of their space-time relationships, making available the actual data to be used in different branches of national economy, such as agriculture, water resources, construction, and other areas of human activity.
- (b) Understanding (analysis and assessment) of natural and anthropogenic changes and variations of climate (including past climate studies and comparison with the present-day state) and of changes in the climatic system's state. Identification of critical factors (natural and anthropogenic) which influence climatic changes and of elements of the biosphere which may have an impact on world climate.
- (c) Prediction of potential climatic variation and variability, qualitative and quantitative forecasts of climatic changes and trends.

Progress in solving such problems as those outlined above requires not only a comprehensive system for monitoring the climate but also a vast research programme which would include computerized studies using climate models. Monitoring the climate and research into climatic variation and variability are closely linked.

4. Various aspects of monitoring

Considering all the above items, a wide range of problems of climate monitoring and data collection relevant to potential climatic changes and variations can be divided into categories as follows:-

- (a) Measurements of basic meteorological values, monitoring atmospheric phenomena and processes characterizing the relevant weather regime (climate). Obtaining climatic data to be used in man's economic activity.
- (b) Monitoring the state of the climatic system. Collection of data characterizing the response of the climatic system and its elements to natural and human impact.
- (c) Monitoring factors (internal and external), affecting the climate and climatic system's state, and their sources. Monitoring anthropogenic factors should be stressed here.
- (d) Monitoring potential environmental changes resulting from climatic changes and variations (physical and ecological), and monitoring indirect indices of climatic variability.

- (e) Obtaining further characteristics required for comprehensive analysis of the environment and climate modelling.

5. Monitoring basic meteorological elements: the existing system.

Category (a) of the preceding section includes the following meteorological data obtained by national meteorological stations: measurements of temperature (including daily extreme values), atmospheric pressure, humidity, wind speed and direction, cloud amount and type and height of cloud base. Measurements of hydrometeorological parameters (sometimes in conjunction with further measurements) permit the monitoring of atmospheric phenomena and processes (turbulence and circulation). Thus measurements of evaporation together with the measurements of the above parameters make it possible to make estimates of water balance.

This category also includes the acquisition of climatic and allied data for utilization in different areas of human activity, i.e. construction, agriculture, transport, energy demand and production, water resources, etc.

Hydrological information on streamflow, snow cover, soil moisture, depth of soil freezing and other elements is also used. These data are obtained at both meteorological (climatological) and hydrological stations and at posts of National Meteorological Centres (NMC) and hydrological services. According to approximate estimates, 40 thousand climatological stations and 140 thousand precipitation stations are functioning all over the world 6.

International exchange of basic meteorological information is one of the main objectives of the WMO World Weather Watch (WWW). The World Weather Watch consists of the Global Observing System, the Global Telecommunication System and the Global Data-processing System. The latter is intended not only for operational current data processing but also for data storage and retrieval.

The WWW data are transmitted over the Main Trunk Circuit (MTC) of the Global Telecommunication System (GTS). The basic synoptic network of WMO observing stations whose data are transmitted over the MTC, consists of about 2 500 surface stations, about 725 radiowind aerological stations and 720 radiosonde stations (1978) 7,8. Every day 2 600 ships' weather reports (from more than 7 thousand ships) and 3 000 pilot reports are received for the purposes of global exchange.

Monthly climatological reports with surface data are transmitted over the GTS from about 1 500 stations (telegrams "CLIMAT") 7,8, and with aerological climate data from over 500 stations (telegrams "CLIMAT-TEMP") 7,8. Climatic data received from some 1 250 surface stations and 430 aerological stations are regularly published in Asheville (USA) on behalf of WMO.

Satellite data are transmitted regularly as well as data obtained through rocket soundings of the atmosphere (up to 60-80 km). Satellite measurements are discussed in Section 10 of this paper.

Observations of the elements characterizing the state of the atmosphere and its interaction with the ocean are expected to increase greatly during the global meteorological experiment and regional experiments within the framework of GARP.

Observations of atmospheric composition also come into this category of monitoring. Atmospheric constituents with an important bearing on climate include carbon dioxide and ozone. It is therefore essential to note any changes that occur in their concentrations. Various pollutants of natural and anthropogenic origin, electromagnetic radiation and thermal pollution may be considered as factors affecting the climatic system and climate (see Section 7).

The number of stations making observations of the amount of atmospheric carbon dioxide is relatively small (only four). Those observations are carried out at the baseline monitoring stations which are remote from the local (natural and anthropogenic) sources of CO₂.

Ozone monitoring is more widespread. Data exchange on the total amount of ozone includes information from approximately 80 stations. Data on the vertical ozone profiles obtained from ozone soundings are presented by 10 stations 9.

6. Monitoring the state of the climatic system

Monitoring the state of the climatic system is close to monitoring the biosphere as a whole (ecological monitoring). However it concerns only those interactions and effects which are directly concerned with climatic change. Monitoring of climate-forming factors comes into this category as well as the monitoring of elements characteristic of responses of the climatic system and its elements to various impacts that may be responsible for climatic changes (see overview paper by Bolin).

First of all this item covers monitoring the state of the underlying surface; determination of albedo, energy and mass exchange between the atmosphere and the underlying surface; measurements of ice cover on seas, rivers and lakes, and sizes of glaciers; water equivalent and distribution of snow cover in lowland and mountainous terrain; the surface of inland water systems; biomass and surface of the vegetation cover; desertification areas; water content in soil and vegetation; observations and the study of the ocean circulation; optical properties and the mass of the atmosphere and atmospheric state.

Observing the state and composition of the atmosphere is fully covered by monitoring the basic meteorological values and other data described in Section 5.

The state of ocean is monitored by measurements of sea surface and subsurface temperature, salinity, chemical water composition, waves and currents at different depths. The measurements are conducted within the framework of the WMO WWW and IGOSS (the WMO/IOC Integrated Global Ocean Station System) by a great number of ships, ocean stations and buoys.

The study of the interaction between atmosphere and ocean is based on measurements of air and water temperature, dew point, wind speed and direction, pressure, clouds and waves and bathythermograph measurements of subsurface temperature of the ocean. During the first GARP Global Experiment (FGGE) similar measurements will be made from supplementary ships, ocean stations and buoys.

The cryosphere affects climatic changes and is itself very sensitive to various impacts. Monitoring the state of the cryosphere includes observations of snow cover, glaciers, sea, river and lake ice, and noting any changes in permafrost zones.

7. Monitoring factors affecting climate

Of great importance is the monitoring of factors which affect the state of the climatic system and climate and the sources of impact factors (i.e. the causes of appearance or changes of the factors). The above factors can be external (with respect to the Earth's climatic system) and internal; and the sources of internal factors can be either natural or anthropogenic.

Factors resulting from the effect of the Sun and cosmic radiation are considered in this study as external impact factors.

Among the factors of the solar effect, the principal focus should be on electromagnetic solar radiation within wide spectral bands including ultraviolet radiation, high-level electromagnetic radiation, corpuscular fluxes of various energies, and magnetic fields.

The intensity of impact factors depends on the solar activity, parameters of the Earth's orbit and the Earth's surface properties (albedo). Solar radiation measurements are carried out by the world actinometric network consisting of more than 900 stations 7. Direct, diffuse and reflected solar radiation are measured; the total atmospheric transparency and albedo of the underlying surface are determined; the total solar radiation and balance of short-wave and long-wave radiation are calculated. Data are sent to the World Centre in Leningrad where they are published every year.

Measurements of ultraviolet radiation are made at ozonometric stations; X-ray and high-level electromagnetic radiation are measured by satellites, and cosmic radiation data are obtained by special stations and satellites.

Within the category of internal factors affecting the climatic system and climate we include thermal emissions and the discharge of different substances into the biosphere or their redistribution among different media. These substances enter the biosphere through natural sources (volcanic eruptions, weathering) and anthropogenic ones (heat output due to man's use of energy, atmospheric pollution and radiation from anthropogenic sources). The above factors are responsible for changes of characteristics of the climatic system, such as water balance, surface albedo, heat and gas exchange between the underlying surface and atmosphere. Changes of the state and properties of the climatic system's elements include the changes of the underlying surface due to anthropogenic reasons (construction of irrigation systems, land-use, changes of forested areas, urbanization) and natural reasons (often together with anthropogenic reasons), such as changes of snow-covered areas and sea-ice boundaries, changes of atmospheric composition and properties (for example, transparency) due to emission of aerosols and other substances. All the above factors have a bearing on climate.

In some cases, a number of these factors may be considered as external with respect to that part of the system where the effects of impact and change are determined. Thus, in a recent study [10] the internal and external systems are distinguished and certain land surface characteristics are considered as a part of the external system.

Measurements of basic components of the atmosphere and of atmospheric pollution are made at the national level by many countries. These measurements form an important part of the Global Environmental Monitoring System.

Measurements of the background level of the atmospheric pollution are carried out at the WMO basic network consisting of 176 stations. Seventy-five of these stations transmit data on the chemical composition of precipitation and 60 provide information about atmospheric turbidity [7].

In the development of the monitoring system, special attention should be paid to measurements of those trace pollutants in the troposphere and stratosphere which are able to affect the ozone content in the stratosphere by changing the natural hydrogen, nitrogen and chlorine cycles. For this purpose, it is necessary to make measurements of nitrogen oxides and chlorofluoromethanes. Special measurements of atmospheric aerosols are therefore made and indirect aerosol data are obtained by comparison of direct and scattered radiation in actinometric observations.

Thermal emissions are estimated from the change of air and water temperature in the zone of emission. Volcanic activity is registered, and a catalogue of all significant volcanic eruptions is compiled.

The factors discussed above can also be observed from satellites.

3. Monitoring consequences of climatic changes and variations

As was noted above, climatic changes and variations can have a marked effect on the state of the biosphere and on man's economic activity.

It is obvious that certain effects occurring in the biosphere as a result of climatic changes and variations (changes of moisture exchange, the total biomass in ecosystems, etc.) can intensify or weaken the action of other factors (because of the presence of positive or negative feedback). Establishment of the monitoring of such changes and their detection appears to be a new important trend in the development of monitoring.

Changes occurring within the elements of the climatic system, and ecological consequences of climate change, may in their turn be sensitive indices of the change, and the characteristics of such changes are often called indirect indices of climatic changes [11].

The biosphere's elements pertaining to high latitudes (polar ice, tundra ecosystems, ecosystems of shelf polar zones), as well as ecosystems of desertification areas and lakes in arid zones, are highly sensitive to climatic change.

Variations of the following factors come into the category of indirect climatic indices: sea, lake and river levels; coastlines; annual sedimentation layers in lakes; annual layers in glacial ice; snow line and snowpack distribution in mountains; boundaries of glacial advance.

A number of ecological data, such as changes of the vegetation cover, crop yield capacity, insect populations, sea microfauna and microflora, spread of plant and animal diseases, etc. may also be placed in this category. In the establishment of observations of such features, it is necessary to exclude other local anthropogenic impacts, for example, a decrease of river and lake stages resulting from the use of water for irrigation.

Sometimes a need arises to obtain additional or supplementary data for comprehensive analysis of the environment and climate modelling. On the other hand, analysis and modelling will allow the most important (critical) impact factors and the most sensitive elements of the biosphere (from the point of view of their consequent effect on climate) to be identified. By this means the development of an efficient climate monitoring system, with emphasis on the acquisition of data relevant to climatic variation and variability, may be placed on a sound scientific basis.

9. Priorities and accuracy of measurement in the development of climate monitoring and climatic data collection services

Priorities of observations of values and factors relevant to climate and in regard to the accuracy of these observations, depend upon the purposes for which the information is intended. Considering the problems referred to in Section 3 above it is obvious that climatic data can be used for the following purposes:-

- (a) solution of applied problems in different areas of human activity - agriculture, construction, energy production, municipal economy, etc.;
- (b) climate modelling for the purpose of determining the climate sensitivity to changes of different parameters, and prediction of climatic changes and variations;
- (c) detection of the foregoing climatic changes;
- (d) isolation of the anthropogenic component of the climatic change, and determination of reasons (sources, factors) for such changes.

The selection of values necessary, in the first instance, for solving various applied problems and the requirements for the accuracy of measurements are determined for each area of human activity, taking account of its specific technical level and regional features. That work, as a rule, is performed by national meteorological services and within the WMO framework. And still more work has to be done for making up deficiencies in the existing networks of climatological stations and creating climatic data banks.

Of great importance is the selection of values and determination of their priorities for the purposes of climate monitoring. This problem was studied thoroughly in connexion with the second objective of the Global Atmospheric Research Programme (GARP) 3. The summary table given below presents the views on the order and accuracy of measurements required at present and in the future (during the international global meteorological experiment and after it) for climate modelling. Necessary and desirable values of the accuracy of measurements are given in the table. The proposals are meant as a supplement to the existing observing system on the basis of the World Weather Watch (WWW).

Table 1
Parameters (according to priorities) and required accuracy
of measurements for the purposes of climate modelling

Parameter	Accuracy
(a) Radiation balance of the Earth-atmosphere system	2-15 Wm ⁻²
(b) Clouds:	
- cloud amount	5%
- cloud top temperature	1 deg C
(c) Sea-surface temperature and heat content of the upper layer (200 m)	0.5-1.5 deg C 1-3 Kcal, cm ⁻²
(d) Snow-covered area and sea-ice extent	(50-100 m resolution)
(e) Surface albedo	0.01-0.03
(f) Precipitation over land and sea	1-3 mm. day ⁻¹
(g) Soil moisture and runoff from the basic river basins	10% of field capacity
(h) Surface temperature (soil and ice)	1-3 deg C
(i) Atmospheric gaseous constituents and particles:	
- Ozone (total content, vertical profile)	1-5% ± 0.5 ppm, 2 km (along the vertical)
- carbon dioxide	± 0.1 ppm
- tropospheric and stratospheric aerosols	5% with respect to volume density
- atmospheric turbidity	1%
(j) Wind stress over ocean	0.1-0.4 dyn. cm ⁻²

Table 1 presents the formulated requirements for the accuracy of measurements of the developing observing system which can, certainly, be used not only for climate modelling but also for other purposes described in Section 3 and in the beginning of this section. Measurements of some parameters, such as sea level, surface currents deep-ocean circulation, sea-ice drift and thickness, will also be necessary, as well as observation of ice polar sheets (changes of boundaries and thickness). Table 1 is based on the publication [3] in which the required and desirable space-time resolution is relatively uniform all over the globe.

It seems, however, that priorities should be also established with respect to space and time resolution. For example, zones of ocean areas having a profound effect on the climate of a particular region, as shown by Marchuk [4], should be given the highest space-time priority of observations. The accuracy of measuring the basic parameter, sea-surface temperature, in such zones should be not worse than 0.2 deg C. Work should preferably be done on the selection of small areas that may be representative from the point of view of climatic conditions of relatively large ocean regions for the purpose of establishing appropriate observations within these small areas.

Observations of changes in the state of biospheric elements which are most sensitive to climatic change (at the global and local scales) should be selected for determination of potential climatic changes (including anthropogenic ones).

Possible consequences and transformations of the most sensitive biospheric elements relevant to potential climatic changes are described in recent publications [12, 13].

The following elements may be regarded as indices of climatic change.

- (a) Average air temperature, first of all for high latitudes.
- (b) Sea-ice extent and boundaries in polar regions.
- (c) Borderlines of glaciers in high and middle latitudes.
- (d) Water level in inland seas and lakes.
- (e) Precipitation and soil moisture.

The problem of identifying the anthropogenic component of potential climatic change seems to be most complicated, as well as the search of reasons for such changes. For this purpose, it is necessary to measure the elements most subject to human impact, i.e. radiation balance elements, atmospheric turbidity, pollution, etc.

It should be borne in mind that local anthropogenic climatic changes are traced more easily than global ones, and climatic changes in polar latitudes are determined with more ease than in low and middle latitudes.

To detect the human impacts, observations should be made with the highest accuracy; this accuracy can be specified with the aid of modelling.

The development of the climate monitoring system and climatic data collection services should be based upon the already available observing systems - national climatological observing networks, the World Weather Watch (WWW) and various observing systems being developed - different national systems for observations of the state of the natural environment, background and local pollution and the Global Environmental Monitoring System (GEMS). Data requirements for each specific purpose would be determined on consideration of the observing systems in operation and the accuracies available. Facilities will also be needed for selecting (filtering) and checking the data required in each case.

The climate monitoring system will undoubtedly require observations and assessment of a number of characteristics and factors not envisaged by the programme of the systems enumerated above.

The climate monitoring and data services concerned with climatic change and variation will require that observations be organized using all appropriate advanced technology including remote sensing techniques, radars, lasers and automatic systems for data processing. Satellites should play a very important role in the development of such a system.

10. Role of satellites in climate monitoring

Possibilities (and efficiency) of the use of satellite systems for obtaining information describing the Earth's climate and the climatic system's state may be grouped as follows:

- (a) Measurements of meteorological parameters and other elements that are important for an understanding of climatic variation and variability in areas covered by surface observations.
- (b) Measurements of the same parameters and elements in areas inaccessible for routine surface observations -
 - (i) continental regions,
 - (ii) oceanic regions
- (c) Measurements of parameters and elements which cannot be observed directly from the Earth's surface:
 - (i) integral characteristics of the underlying surface (albedo, values characterizing energy and mass exchange between the underlying surface and the atmosphere);
 - (ii) some components of the radiation balance of the Earth-atmosphere system (reflected solar radiation and long-wave outgoing radiation of terrestrial objects);
 - (iii) corpuscular and high-level electromagnetic solar and cosmic radiation.
- (d) The use of satellites for operational data transmission from inaccessible regions of the globe.

Taking into account the data provided by surface based observing systems, an assessment may be made regarding the priorities for the use of satellite systems for the requirements set out in (a), (b) and (c) above. The result of such an assessment is given in Table 2.

Table 2

Priorities in the use of satellite systems for
obtaining climatic data (the order is denoted
by Roman figures)

Type of use	(a)	(b) (i)	(b)(ii)	(c)(i)	(c)(ii)	(c)(iii)
Priority	III	II	I	II	I	I

Current observations from satellites provide information about the most important meteorological elements, such as cloud and wind fields, air temperature and humidity at different altitudes; sea-surface temperature; sea-ice extent (boundaries and snow-covered area); vegetation-covered areas (and their characteristics); plankton-covered areas of the ocean; soil-moisture content; location of precipitation areas and their intensity; and components of radiation balance (see, for example, 13, 14, 15).

The satellite sub-system constitutes a part of the WWW Global Observing System. Information is received from near-polar orbiting and geostationary satellites.

Cloud fields have been identified for more than 10 years; it is necessary to increase the accuracy of determination of the cloud top height.

Temperature profiles are determined by analysing infrared or microwave data in the absorption bands for gases with known concentrations (for example, carbon dioxide). The accuracy of determination of temperature profiles amounts to 2-3 degrees centigrade.

The sea-surface temperature is determined from measurements of the radiation in the infrared band; the accuracy of measurements is of the order of ± 1 to 1.5 deg C and it is limited by the absorption of radiation by clouds, dust and other obstacles. It should be noted that determination of the sea-surface temperature is of great importance since a knowledge of this value makes it possible to evaluate approximately the heat content of the upper ocean layer and to use this value for quantitative estimates concerning the turbulent heat and water exchange between the atmosphere and the ocean. In this connexion, the accuracy of determining the temperature of the sea-surface layer should be increased up to tenths of a degree centigrade.

The accuracy of determination of the land temperature is less stringent than that of the sea-surface temperature.

Limits of ice and snow cover are determined in the visible range with sufficient accuracy. Measurements in the visible and infrared ranges make it possible to determine different types of polar ice, and by measurements in the microwave range (on wavelengths of about 1.5 cm), on ice fields and ice-free water, thickness and age of ice are obtained.

Some surface characteristics (vegetation, total amount of plankton) are determined using multispectral images.

The determination of soil moisture and precipitation is feasible with the aid of microwave radiometers.

Satellite observations may be widely used for measuring a number of the climatic system's elements and other parameters affected by man's activities. Human impacts may affect the atmospheric turbidity, increase the amount of carbon dioxide and create pollutants affecting the ozonosphere (chlorofluoromethanes, nitrogen oxide).

Dust layers (turbidity) are identified from satellites by taking pictures of the horizon area and measuring the angle distribution and polarization of the scattered solar radiation.

The total amount of gaseous components of the atmosphere, such as water vapour, carbon dioxide and ozone can be determined using the spectrometry of absorption bands of the emitted heat radiation and reflected solar radiation. Determination of the vertical ozone distribution is also possible.

The interaction between ocean and atmosphere, and albedo of the sea surface can be affected by oil pollution due to formation of surface films interfering with the mass exchange between ocean and atmosphere. Detection of oil films from satellites is possible using multispectral images.

The role of satellites to provide information about the anthropogenic changes of land is very great. Satellite data make it possible to estimate changes of vegetation cover due to forest felling, desertification and changes in the character of crops. Knowledge of the changes helps to explain the changes of surface albedo. Urbanization also affects the albedo. Large irrigation structures and redistribution of water resources influence the nature of the water balance as well as the surface albedo; changes of snow cover in towns and industrial regions are easily traced from satellites. All this information is obtained by interpreting satellite images (in different intervals of the visible and infrared ranges).

Suomi 10 suggests the determination of the total amount of released anthropogenic energy from artificial light (at night) using a statistical relationship between these two values.

Components of the radiation balance corresponding to the reflected solar radiation (in the spectral range of 0.3-3.0 μ) and thermal radiation from the Earth's

surface (in the range of 3-100 μ) depend upon the anthropogenic factors (anthropogenic changes of the surface albedo and the rate of thermal radiation of terrestrial objects).

All components of the radiation balance are determined from satellites, and some of them can be determined with even more accuracy than from the Earth's surface.

Anthropogenic changes in the near-Earth cosmic space can also be determined using satellite observations. For example, the artificial radiation belts were defined by spaceborne radiometric equipment.

11. The role of monitoring in the development of criteria on the acceptability of anthropogenic impacts on the climatic system

Analysis of potential anthropogenic climatic changes and variations and of the reasons and sources of anthropogenic impacts directly or indirectly connected with climatic changes makes it possible to fix limits for the impact values which would keep the climate and climatic system within the framework of natural fluctuations (for example, within the time interval of the last century) on the global or local scale. It is obvious that such limiting criteria may be formulated for separate factors and for combinations of different factors.

Thus, the above criteria may refer to limitation of the carbon dioxide concentration in the atmospheric air (or of the rate at which carbon dioxide enters the atmosphere), to limitation of penetration of different pollutants (for instance halogen hydrocarbons) and of anthropogenic heat into the atmosphere, and to establishment of admissible limits (upper and lower) of dustiness of the troposphere and stratosphere. A violation of criteria formulated in this manner, would be expected to result in noticeable changes of climate.

Formulation of such criteria implies the determination of critical (potentially most dangerous) impact factors affecting the environment, and establishment of admissible values of the impact on the most sensitive biospheric elements and the biosphere as a whole.

The capability of identifying such effects and impacts with the aid of the monitoring system (together with climate modelling) and the arrangement of appropriate measures to be taken in accordance with the established criteria will help to eliminate the danger of undesirable and even disastrous climatic changes.

12. Summary

The existing viewpoints on the climate and climatic data collection services expressed by experts from different countries and international organizations are described in this report 3, 6, 9, 10, 16, 17

Special emphasis is laid on the need to single out from among a great number of various characteristics of the natural environments and influencing factors the essential ones required to solve the basic problems - obtaining climatic data for solving the applied problems, determination of characteristics of the climatic

system's state and factors of the impact on this state - the study and understanding of climatic changes and variations, the identification of human impacts and effects of climatic changes. Monitoring these changes in the biosphere relevant to the climatic change is a new trend in monitoring.

The next step is the development of a monitoring scheme for the above purposes. This scheme should be as detailed as that developed for the purpose of climate modelling ⁷.

A detailed monitoring system should (together with climate modelling) be aimed at identification of those natural and man-made climatic changes which would seriously affect the biosphere so that effective measures may be taken to prevent undesirable or even disastrous climatic changes.

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HUMAN ACTIVITIES THAT AFFECT CLIMATE

R.E. Munn* and L. Machta[/]

1. Introduction

Mankind has been modifying the environment for several thousand years, and some of these modifications affect climate. For example, whenever a forest is cleared or a road is built, the local heat and water budgets are changed. These changes were first investigated more than 50 years ago by German scientists such as R. Geiger ^[1] who laid the foundations for present knowledge of microclimate and city climate. There are three ways in which mankind affects climate:

- (a) by changing the composition of the atmosphere, including changes in the concentrations of water;
- (b) by releasing heat into the atmosphere;
- (c) by changing the physical and biological properties of the underlying surface.

There is no doubt that these processes help to produce local climatic anomalies; for example, a pall of pollution changes the atmospheric radiation balance over a city, construction of a reservoir changes the surface radiation and energy balances, and reduces the frictional wind drag. In addition to these local effects, however, there has been growing speculation since the 1930s that climate modification might be taking place or might someday become significant on the global scale. This implies that local and regional perturbations collectively could influence weather patterns in other parts of the world or that climatic change could take place globally in the first instance, as would be the case in the stratosphere.

Three major obstacles confront the investigator searching for evidence that mankind has affected climate:

- (a) the natural variability of climate;

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- (b) the existence of multiple impacts and interactions.
- (c) the large scale spatial organization of the world's land surfaces, of many of the human impacts and of the atmospheric general circulation.

Climate varies so much that it is difficult to answer the question: what would contemporary conditions be like if mankind did not exist? Even in the case of local anomalies, this is sometimes a troublesome question. Many cities are located in irregular terrain (on coastlines, in river valleys, etc.) which results in complex local climatic patterns; moreover, these cities were built long before the first weather observations were taken. As a consequence, the investigator has no reference state with which to compare current conditions. In the case of global climate, the non-impacted reference state is even more difficult to estimate. These questions have been considered by Munn and Rodhe [2] and Pittcock [3], who recommend that for interpretation of climatic trends at a single or a cluster of stations, every effort should be made to identify the effects of trends in the large-scale weather patterns. For example, Pittcock [3] could associate an increase in precipitation on the west coast of North America between 1941 and 1970 with a shift, perhaps temporary, in the annual mean latitude of maximum sea-level pressure; there was no need to invoke the hypothesis that emissions of cloud condensation nuclei from industrial sources had increased during the 30-year period along the west coast.

As for the existence of multiple impacts and interactions, mankind often modifies the geometry of the surface of the Earth, changes the surface water budget, and releases particles, gases and heat into the atmosphere all at the same time. The associated time lags may be different in each case. Furthermore, there may be interactions, in which one of these factors amplifies or dampens the magnitude of another. For example, overgrazing may affect the radiative properties of an area, modifying the heat and water budgets, and changing the rate of re-entrainment of soil particles into the atmosphere. Unfortunately, there is little possibility of performing controlled geophysical experiments in which all but one or two of the factors affecting climate are kept constant. An alternative approach is through the use of models, discussed in the overview papers by Gates, Marchuk, Mason, and Williams et al.

Finally, the pattern of human intervention is far from randomly distributed around the world. The impacts are concentrated over the continents, particularly in urban/industrial and agricultural areas, and are superimposed on different kinds of regional climatic patterns.

Because of these complexities, an answer to the following important question is not at all obvious. If average world temperatures were to increase by, say, 1 deg C (which would undoubtedly change the world pressure and rainfall patterns and thus the pattern of world temperature), how many years' data would be required to detect the warming with 95 per cent confidence?

The subject of this paper is clearly of very wide scope and accordingly it is presented in two main parts as follows:

- Part I. By Munn, consists of Sections 2-7 and covers the main human impacts on climate, excluding mankind's interference in the atmospheric carbon dioxide (CO₂) balance.

Part II. By Machta, consists of Section 8 and deals comprehensively with those aspects of climatic change which are related to the carbon dioxide balance. The subject has many important ramifications and is also referred to in the overview papers of Baumgartner, Bolin, Flohn, Gates, Mason and Williams et al.

2. Human impacts on the composition of the atmosphere, and mechanisms for climatic effects

2.1 Basic causes

Mankind modifies the atmospheric concentrations of trace substances in three ways:

- (a) by emitting gases and particles, particularly the combustion products of fossil fuels, from towns and industrial areas;
- (b) by agricultural burning of stubble, etc., and by forest and grassland fires started accidentally;
- (c) by ploughing and overgrazing, resulting in dust being lifted up into the atmosphere during dry, windy weather. The Northeast Trade Winds carry dust from North Africa to the West Indies, for example.

The first of these activities has been widely studied, but in the other two cases there is little global information on source strengths and climatic effects. This is partly because natural sources, e.g., evaporation of sea spray, sometimes predominate.

Particles and trace gases may affect climate in three ways:

- (a) by changing the atmospheric radiation balance, modifying the thermal and dynamic structure of the atmosphere;
- (b) by upsetting the stratospheric photochemical ozone budget, modifying the thermal and dynamic structure of the stratosphere (see Section 3);
- (c) in the case of particles, by disturbing the condensation nuclei populations, with possible effects on cloudiness and precipitation processes.

2.2 Gases

The trace gas that has been most widely suggested as a cause of climate change is CO₂ but other gases such as water vapour, the chlorofluoromethanes, carbon tetrachloride, methane, nitrous oxide and ammonia 4, 5, contribute to the so-called greenhouse effect. In the absence of clouds, the sun's short-wave radiation passes downward through the atmosphere with little attenuation. However, the Earth's long-wave radiation is absorbed selectively in several infrared bands by these gases. This warms the lower atmosphere, all other factors remaining constant. When clouds are present, the radiative transfer processes are more complicated but the same greenhouse principle applies. The phrase "all other factors remaining constant" is important. In fact, a change in temperature modifies the dynamics of the atmosphere, and there is no possibility of performing a laboratory or simple outdoor experiment to study the various feedbacks that may exist.

Although concentrations of greenhouse gases are highest in towns and industrial areas, the purely local climatic influences are rather small and are usually masked by other factors. The main effect is global involving the total depth of the atmosphere. Estimation of the magnitude of the warming to be expected, if the concentration of a trace gas were to increase by a designated amount, can only be obtained from numerical models of the atmosphere. Because current simulations do not include the level of detail to be found in the real atmosphere, the absolute values of the greenhouse effects are somewhat uncertain. Nevertheless, the predicted potentials of various gases may be compared on a relative scale. Flohn's summary [6] of studies by Wang et al. [4] and Augustsson and Ramanathan [5] is given in Table 1, which shows that several gases might contribute to greenhouse warming. In particular, a 100 per cent increase in stratospheric water vapour could be significant.

For most of these gases, there have been upward trends in recent years in both industrial production and in atmospheric concentrations. For CFCl_3 (trade name Freon 11), for example, measurements from Cape Grim, Tasmania show an average increase of 15 per cent per year during the period 1976-78 despite the fact that global production of this substance has decreased since 1974. See Figure 1 [7].

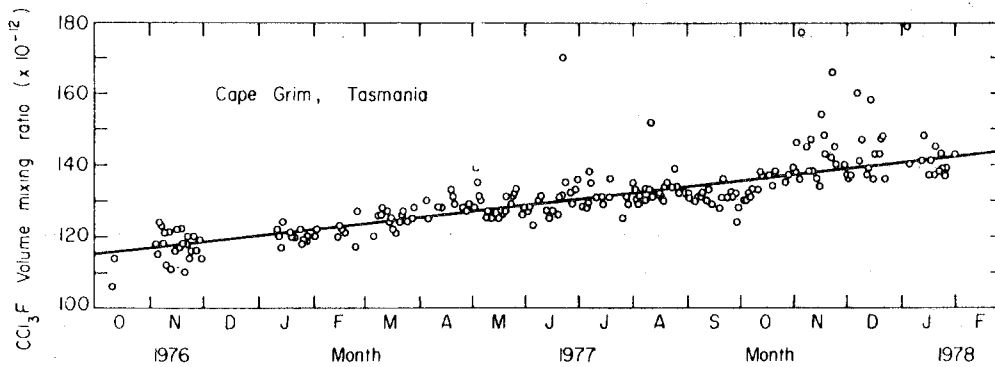


Figure 1. Daily mean atmospheric concentrations of CFCl_3 (trade name Freon 11) at Cape Grim, Tasmania [7].

Finally, mention should be made of oxygen and nitrogen. Ryther [8] believes that if all photosynthesis in the oceans were to stop suddenly, at least a million years would elapse before atmospheric oxygen concentrations decreased by 10 per cent. Certainly there has been no detectable change in concentrations since 1910 [9]. Dobrodeev [10] notes that although the present consumption of oxygen through the burning of fossil fuels significantly exceeds the total consumption by natural processes, the burning of all known fossil fuel reserves would reduce the atmospheric oxygen concentrations by only a small fraction. The concentration of atmospheric nitrogen, N_2 , even more abundant than oxygen, is unaffected by human activities.

2.3 Particles

The average residence time of a particle in the lower atmosphere is a few days. The highest concentrations of suspended particulate matter are therefore located within 1 000 km of source regions, as is evidenced by a rapid drop-off of particulate concentrations downwind of continents. Because the exchange time between the

northern and southern hemispheres about 1 year, the two hemispheres can be considered as independent with respect to particulate loadings. In the stratosphere, the average residence time of a particle is at least a few months, so that stratospheric particles become of global significance.

Table 1

Estimated change in global average surface temperature arising from changes of atmospheric constituents (after Wang *et al.* [4], Augustsson and Ramanathan [5], indicated as W and AR), based on a one-dimensional radiative-convective model assuming: (a), a fixed cloud-top height; and (b), a fixed cloud-top temperature in the model [6].

Constituents	Initial concentration	Increase in percent	Greenhouse effect (°C)		
			fixed cloud-top		AR
			height	temperature	
CO ₂ (carbon dioxide)	320 ppm*	+ 100	2.0	3.2	AR
CO ₂ (carbon dioxide)	330 ppm*	+ 25	0.5	0.8	W
O ₃ (ozone)	0.34 cm**	- 25	-0.3	-0.5	
H ₂ O (water vapour in stratosphere)	3 µg/g***	+ 100	0.6	1.0	
N ₂ O (nitrous oxide)	0.28 ppm	+ 100	0.4	0.7	W
CH ₄ (methane)	1.6 ppm	+ 100	0.2	0.3	
CFC1 ₃ + CF ₂ Cl ₂ (F-11 + F-12) (chlorofluoromethanes)	0.2 ppb****	factor of 20	0.4	0.5	
CCl ₄ + CH ₃ Cl (carbon tetrachloride + monochloromethane)	0.6 ppb	+ 100	0.01	0.02	W
NH ₃ (ammonia)	6 ppb	+ 100	0.09	0.12	
C ₂ H ₄ (ethelene)	0.2 ppb	+ 100	0.01	0.01	
SO ₂ (sulphur dioxide)	2 ppb	+ 100	0.02	0.03	

* ppm = parts per million by volume

** cm = depth that would be occupied by the total ozone in the atmosphere if it were at sea level temperature and pressure

*** µg/g = micrograms of water vapour per gram of air

**** ppb = parts per billion by volume

Mankind has been contributing significantly to the particulate loading of the atmosphere for many centuries through agricultural and urban/industrial activities. Estimated changes in particulate concentrations in London are shown in Figure 2 [11], which reveals a deterioration in the 17th and 18th centuries and an improvement in the 20th [11]. This behaviour is probably quite typical of many European cities. A wood shortage beginning near the end of the 16th century led to the use of coal for home heating and cooking, and a major rise in particulate and sulphur dioxide (SO_2) concentrations in the 17th century. (Because the gas SO_2 is converted to sulphates within a day or so, it contributes to the regional particulate loading.)

At the turn of the century, smoke from home fires in Brighton, England could sometimes be seen crossing the coast of France [12], and the air quality in the so-called "black country" of central England and in North American cities like Detroit and Pittsburgh was intolerable by present standards. However, the use of more efficient methods of combustion, cleaner fuels, smoke removal equipment and taller chimneys has led to a steady improvement in air quality in the last few decades in many towns, even though fuel consumption has increased in many areas. There are exceptions of course, particularly in the developing countries: some cities are growing rapidly with little control of apartment incinerators and other major sources of particulates.

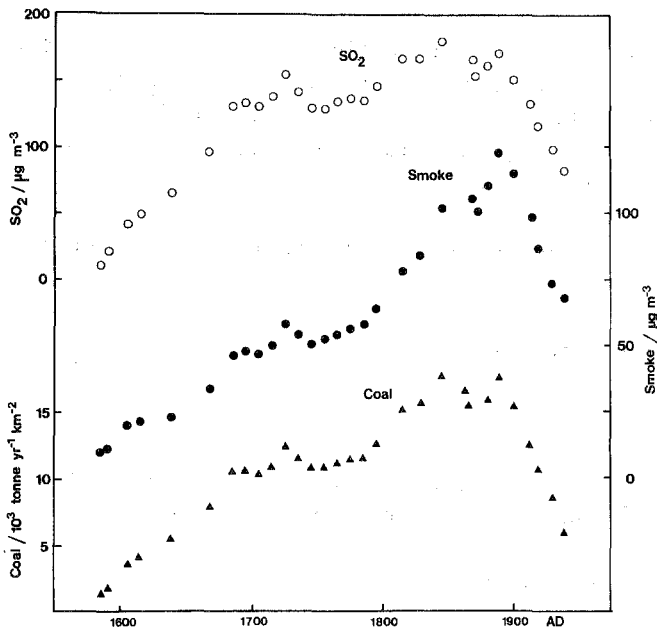


Figure 2.

Decadel mean sulphur dioxide and smoke concentration in the London air as determined from coal imports [11].

Although the black smoke above and downwind of urban-industrial areas has disappeared in Europe and North America, it has been replaced by brown haze which sometimes covers very large areas indeed. Urban emissions of photochemically active gases and hydrocarbons have been increasing, leading to increases in sulphate, nitrate and phosphate particulates, sometimes 500 to 1 000 km distant from source regions. As an example, Vickers and Munn [13] found a significant increase in summer haziness in Eastern Quebec and the Canadian Atlantic provinces since 1970,

probably because this part of Canada is downwind from large urban areas. Similar summer trends have been observed in Ohio 14, and there has been some concern about the widespread sulphate hazes that sometimes cover western Europe as well as eastern North America 15. In these regions, there are many personal testimonies to the fact that frequencies of occurrences of exceptionally high visibilities have declined during living memory. In contrast with summer, the Canadian winter data analysed by Vickers and Munn 13 showed a significant decrease in haziness in the last 25 years due to a reduction in the emissions of particulate matter; in addition, the sun is not strong enough in winter to generate much photochemical activity.

Away from industrial regions, natural and agricultural sources also contribute significantly to the particulate loading of the atmosphere. Dittberner 16 has published Table 2, which provides an estimate of the relative global strengths of natural and man-made sources, from which it may be seen that natural emissions predominate. There is considerable interest in estimating long-term changes in these source strengths but this has been attempted in only a few cases. One example is the dust veil index 17, 18, a reasonably reliable indicator of volcanic activity, and of particular significance for the stratosphere (see Section 3). With respect to forest fires, the fragmentary evidence suggests that in the temperate zones, the frequency of fires has increased since the last century but that fires are more quickly brought under control 19. There is much speculation but few data about trends in developing countries.

A.W. Hogan 20 and associates have been measuring the surface concentrations of condensation nuclei around the world. An example is given in Figure 3 21, which shows isopleths of average concentration of condensation nuclei over the Pacific Ocean. A background value of slightly less than 300 particles per cubic centimetre of surface air is to be found in the Central Pacific.

The effects of particles on the atmospheric radiation balance depend on a number of factors:

- (a) the size distributions of the particles;
- (b) the shapes of the particles;
- (c) the scattering, reflection and radiative properties of the particles (carbon particles behave differently from quartz particles);
- (d) the vertical distributions of particles;
- (e) the relative humidity (some particles are hygroscopic, for example);
- (f) time variabilities in all of the above factors.

Table 2

Particulate production estimates (diameter < 5 μm)

	10^6 tonnes yr^{-1}	Per cent
<u>Anthropogenic input</u>		
<u>Fossil fuels</u>		
Gases (subsequently converted to particles in the atmosphere)	311	45
Particulates	54	8
<u>Wind-blown dust</u>	180	26
<u>Agricultural burning</u>		
Hydrocarbons	72	10
Particulates	62	9
Nitrates	7	1
<u>Fuel wood</u>		
Particulates	4	1
<u>Forest fires</u>		
Particulates	<u>2</u>	<u>0</u>
	692	100
<u>Natural input (excluding volcanoes)</u>		
Sea salt	500	46
Sulphates (natural decay)	335	31
Wind-blown dust (natural decay)	120	11
Hydrocarbons (natural decay)	75	7
Nitrates (natural decay)	60	5
Forest fires (lightning)	<u>3</u>	<u>0</u>
	1093	100
<u>Volcanic input</u>		
Dust	25-150	37
Sulphates	<u>42-255</u>	<u>63</u>
	67-405	100
	=====	
Grand Total	1852-2190	

Source: 16.

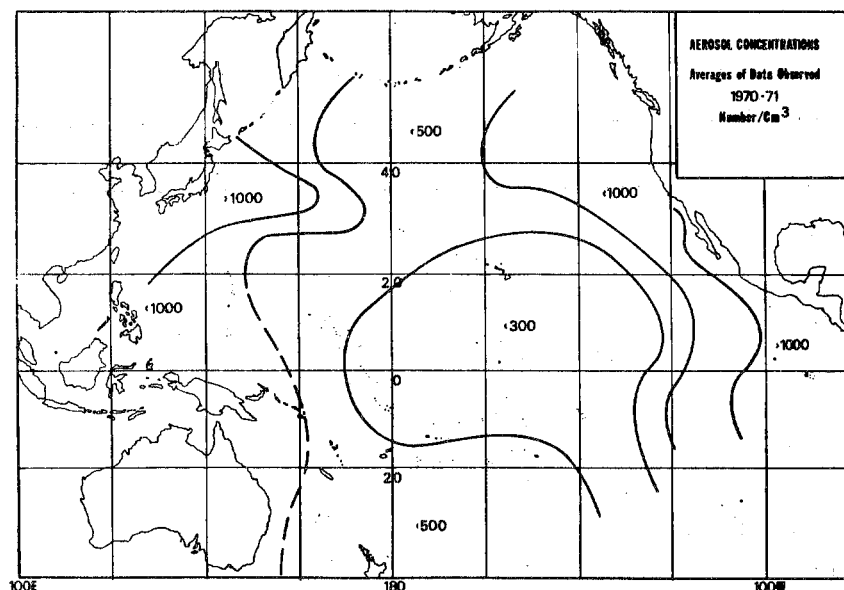


Figure 3. Average numbers per cubic centimetre of condensation nuclei in surface air over the Pacific Ocean in 1970-71 [21].

Most data sets are incomplete, so that it is impossible to verify experimentally the more realistic models of radiative transfer. In fact, Twomey [22] has suggested that "the time and energy put into discussion of secular trends in atmospheric aerosol concentrations perhaps outweigh the time and energy which have been put into measurements". However, Kondratyev has organized a major data-gathering programme in the U.S.S.R. [23]. Termed CAENEX (the Complete Atmospheric Energetics Experiment), the programme has already yielded data sets for conditions over a desert, over water and over a city.

The sun's radiation is attenuated as it passes through the atmosphere. Part of the solar beam is absorbed by gases, particles and clouds (to be re-radiated as long-wave radiation), another part is scattered and reflected upward to space and downward to the Earth's surface as diffuse radiation; the remainder reaches the ground directly. Some of the direct and diffuse radiation striking the Earth's surface is reflected upward (this fraction is called the surface albedo). The remainder is available to heat the ground, melt ice, and evaporate water.

An increase in the particulate loading of the atmosphere leads to:

- (a) a change in the amount of solar radiation scattered back to space (causing the mean atmosphere/Earth temperature to change);
- (b) more absorption of solar radiation in the atmosphere (causing atmospheric temperatures to increase);
- (c) less solar radiation reaching the surface of the Earth, (causing ground temperatures to decrease);

- (d) an increase in the ratio of diffuse to direct solar radiation (this has been found experimentally to lead to an increase in surface albedo, and thus to surface cooling) 24.

Solar radiation absorbed by the atmosphere and the Earth's surface is re-radiated as long-wave radiation, which criss-crosses the atmosphere in many directions. An increase in particulate matter therefore produces long-wave greenhouse warming. For a sharply-capped haze layer or a cloud, there would, however, be cooling at the upper surface.

The net effect of suspended particulate matter on the radiation balance of the lower atmosphere is difficult to assess even on a single cloudless day. To simplify the problem, many models ignore long-wave radiation, which is known to be small compared with solar radiation during the day, although it cannot be ignored at night. In general terms, each major source region should be examined separately, the radiative effects being different over western Europe from those over North Africa. A model which uses an average particulate composition for the entire globe is not a realistic one.

One of the few relevant experimental investigations is that of Idso and Brazel 25 who measured the daytime radiation components at the Earth's surface in Arizona during dust storms. They found that small increases in dustiness tended to raise the surface temperature. As dustiness increased, however, warming was ultimately replaced by cooling, although at concentrations much greater than would ever be encountered as a result of human activities.

Numerical models of cities, which ignore the long-wave radiation components but include heating and cooling effects due to convection and evaporation, suggest that suspended particulate matter leads to warming of the air layer over the city; an increase in surface wetness or in surface albedo enhances this effect 26.

Early studies of global climate emphasized the fact that particulate matter increased the scattering of solar radiation backward into space, resulting in a net cooling of the atmosphere/Earth system. More recently, Flohn, Kellogg and Mitchell have challenged this view. Kellogg, for example, believes that the albedo is an important variable; the higher its value, the more likely that an increase in particulate concentrations will warm rather than cool the Earth/atmosphere system 27. Because the highest albedo values are over the continents where the atmospheric particulates are concentrated, differential warming of areas such as western Europe and eastern North America is likely. (This possibility is not excluded, of course, of cooling over the oceans although there is need for more theoretical and experimental studies.) As a simple illustration of this principle, a plume of black smoke would increase the albedo over a water surface and thus cause cooling whereas the same plume would decrease the albedo over a snow surface and cause warming.

2.4 Krypton-85

Atmospheric concentrations of Krypton-85 will increase in future decades due to the widening use of nuclear energy. This will decrease the electrical resistance of the lower atmosphere, by as much as 10 per cent within 50 years according to Boeck

28. The effect on climate is unknown but there could conceivably be a change in thunderstorm activity and precipitation patterns. This possible problem for the future deserves further study.

3. Special considerations relating to the stratosphere

The stratosphere requires special consideration because it is chemically as well as dynamically active. Ozone absorbs solar radiation, heating the stratosphere and generating large-scale wind fields. Thus a change in the rate of photochemical production or destruction of global ozone ought to be associated with a modification in the dynamics of the stratosphere.

Several natural and man-induced mechanisms for perturbing the stratosphere have been suggested:

- (a) Natural mechanisms (volcanoes; extra-terrestrial events such as solar flares or explosions of supernovae);
- (b) Man-induced mechanisms: Stratospheric releases (aircraft emissions; nuclear explosions); Ground-level releases (chlorofluoromethanes; N₂O from fertilizers and/or nitrogen-fixing vegetation; other greenhouse gases such as CO₂ and methane).

In each case the stratospheric radiation budget might be affected:

- (a) Directly through changes in the concentrations of particles or greenhouse gases; or
- (b) Indirectly through changes in the rate of photochemical production or destruction of ozone.

3.1 Trends in the abundance of trace substances in the stratosphere

A recent analysis of ozone trends by Angell and Korshover provides no evidence for a human impact between 1958 and 1976 29. There seems to be an 11-year solar cycle 30 as well as an apparent connexion with volcanic eruptions, but this latter effect may be instrumental; the Dobson spectrophotometer observations are degraded by the presence of stratospheric dust veils. A special feature of stratospheric ozone is that its natural variability from day-to-day and from place-to-place is so great that trend determination is difficult; if mankind were to wait for experimental evidence of ozone depletion of 5 per cent with 95 per cent confidence, say, it would already be too late to prevent an extended period of such conditions.

Turbidity measurements made at high-altitude observatories over several decades reveal the persistence of dust from volcanic eruptions. The most widely cited example, the eruption of Krakatoa in the last century, produced a readily detectable dust veil and brilliant sunsets lasting several years. When the effects of volcanic eruptions are removed from a long series of turbidity measurements, there remains no strong evidence for trends; see for example, 31. One possible exception is turbidity (as measured by a pyrhelimeter) at Mauna Loa, Hawaii; winter values

have returned to the levels existing prior to the volcanic eruption of Mount Agung in 1963 but summer values remain slightly depressed [32].

Vapour trails from high-flying aircraft are visible from time to time. This has led to speculation that there may be increases in the frequencies of cirrus clouds over major air routes, and in the concentrations of stratospheric water vapour. Both of these factors would affect the atmospheric radiation budget. The data are inconclusive, but it is likely that the impact is as yet minimal, being limited to an occasional hastening, by an hour so so, of the development of naturally occurring high cloud. Measurements of stratospheric water vapour contain great variability in space and time, making it impossible to determine trends.

There is little information on stratospheric concentrations of other trace substances and no information on trends. One of the complicating factors is that the concentration of a trace substance could change merely because of changes in photochemical destruction or production rates; this could occur through dynamic processes, in which the substance was transported to levels where the photochemical processes were more (or less) active.

3.2 Stratospheric photochemistry

The classical photochemical explanation for the ozone layer given by Sidney Chapman in 1930 has had to be modified several times since 1960 with the recognition of additional chemical and meteorological mechanisms. The most recent views are summarized in the Proceedings of a 1978 WMO Symposium [33]. Uncertainties in the values of the photochemical rate constants have now been mainly eliminated and values to within ± 25 per cent have been determined independently by two or more laboratories in most cases. There remains the problem of knowing whether all of the important reactions have been included in present sets of equations. There is also the difficulty of modelling a large number of photochemical reactions in a dynamically active stratosphere. The present generation of models predicts that:

- (a) continued use of chlorofluoromethanes and nitrogen fertilizers could cause a small long-term depletion in stratospheric ozone (about 15 per cent by the middle of the next century);
- (b) the net effect of SST aircraft might result in a small increase in stratospheric ozone, rather than a decrease as previously predicted;
- (c) because of feedback relations, an increase in CO_2 concentrations could have a significant effect on stratospheric ozone, but the sign of the effect is still uncertain; (Groves *et al.* [34] predict that cooling of the upper stratosphere would cause an increase in ozone.);
- (d) an increase in CO concentrations would cause a decrease in stratospheric ozone;

3.3 Climatic effects of stratospheric perturbations

Above-average ozone concentrations are associated with below-average surface air temperatures; the winter of 1976 was cold in the northern hemisphere, and ozone values were high. However, the above-average ozone concentrations did not "cause" the cold weather in any direct way. There is in fact no easy method of identifying the climatic effects induced by perturbations in the ozone layer.

There is, however, considerable preoccupation with the question of estimating the direct radiative effects of an injection of particles into the stratosphere. Here the example is frequently given of the eruption of Mount Agung. Temperatures at heights of 18 and 20 km over Australia rose as much as 5 deg C and took as long as four years to recover to normal values [35].

Based on the intensity of global volcanic activity, Lamb [17] and Bray [18] have developed dust veil indices and have published annual values dating back to 1750. Statistically significant correlations with meteorological parameters such as mean surface temperature have been found but tests using independent data are not completely successful, e.g., [17, 36, 37]. Alternatively, Schneider and Mass [38] and Bryson and Dittberner [39] have used the dust veil index with some success in climatic models to estimate the behaviour during recent decades of the global annual mean surface temperature. In addition, several models have been developed to study the radiative effects of stratospheric dust, e.g., [40, 41, 42]. Even though the stratosphere would appear to be easier to model than the lower atmosphere, nevertheless Robinson [43] emphasizes the complexity of the problem, noting that to undertake a realistic simulation, "it is necessary to know the exact nature of the size distribution of the particles, their complex refractive index over the whole solar spectrum, and the albedo of the underlying surface-atmosphere-cloud system, again over the whole solar spectrum. This we do not know."

4. The release of heat into the atmosphere

When averaged over the globe, the heat generated by human activities is a trivial fraction of the net solar radiation at the Earth's surface. A comparison of the magnitudes of several energy sources is as follows [44, 45]:

Solar radiation at outer edge of atmosphere	350 W m ⁻²
Net solar radiation at the Earth's surface	160 W m ⁻²
1970 energy production distributed evenly over the globe	0.016 W m ⁻²
1970 energy production distributed evenly over the continents	0.054 W m ⁻²
Annual continental net photosynthetic energy	0.16 W m ⁻²
Annual global energy flow from the Earth's interior	0.06 W m ⁻²

Heat from major United States cities

20 to 40 $W m^{-2}$ (summer)
70 to 210 $W m^{-2}$ (winter)

Compared with other energy sources, the sun predominates on the global scale. However, the heat generated by human activities can sometimes be of the same order of magnitude as, or even exceed, the net solar radiation locally or even regionally.

5. Human impacts on the Earth's surface, and mechanisms for climatic effects

The surface of the Earth has been greatly altered by mankind. A major change began in western Europe about 5 000 B.P. with the development of a shepherd-farmer culture, resulting in gradual clearing of the forests, and changes are continuing even to this day. Big cities have existed for a long time but only in this century has there been rapid expansion, resulting sometimes in the merging of several urban areas into megalopolises. In recent times too, there have been major hydro-electric, irrigation and drainage projects, both in industrialized and developing countries. These developments have affected local and regional climates. Some ancient civilizations disappeared because of dwindling food and water supplies, partly due to inadvertent modification of local climate by mankind (overgrazing, soil erosion, etc.) [46]. On the other hand, there are examples of good climatic planning through the terracing of slopes and the construction of shelterbelts (first introduced in the 18th century). Today there is considerable knowledge of good land-use management practices that minimize harmful effects of climatic changes. Sometimes, in fact, the surface of the Earth is modified deliberately to improve local climate with respect to some human activity. For example, with respect to orchards that are susceptible to frost damage, the micro-terrain may be modified to improve down-slope air drainage and thus reduce the frequency of frost.

5.1 Albedo

Typical values of surface albedo are given in Table 3 [45]. The world's open oceans have the smallest albedos, cover the largest area, and are the most difficult to modify. Global average albedo is therefore relatively small and can be affected only slightly by human activities. Nevertheless, regional variations over the continents can be significant and can be modified by mankind. Baumgartner et al. [47] have produced the climatological maps of surface albedo given in Figure 4, which show large spatial and seasonal variations. As in the case of atmospheric particulates, realistic models of the general circulation should take these space and time variations into account.

The large-scale changes in the albedos of land surfaces that have taken place over the centuries have had a variety of possible causes, examples of which are listed in Table 4.

Based on some estimates by Flohn [48], Otterman [49] has computed the global average surface albedo at the present time and 6 000 years ago with the following results:

	<u>Today</u>	<u>6 000 years ago</u>
Northern hemisphere	0.157	0.138
Southern hemisphere	0.151	0.143
The world	0.154	0.141

The increase in albedo in the last 6 000 years should have caused a drop of 0.13 deg C in global surface equilibrium temperature according to Flohn 50, all other factors remaining unchanged. In this connexion, Hummel and Reck 51 have a model which predicts that if the amount of arable land were increased by 1 per cent and its albedo changed from that of black soil (0.07) to that of crops (0.25) for one-third of the year, the Earth's surface temperature would be decreased by 1 deg C. By a similar line of reasoning, the man-made lakes and reservoirs (estimated to cover 300 000 km²) may have increased the surface temperature by 0.4 deg C. However, albedo changes are concentrated in only a few regions of the Earth (perhaps only 10 per cent of the Earth's surface) so that climatic effects would in the first instance be regionalized.

Table 3

Selected values of surface albedoes 45

Surface	Albedo (per cent)	Surface	Albedo (per cent)
Fresh snow	85-90	Dry, ploughed field	10-15
Desert	25-30	Wet fields	5-10
Dried grass	20-25	Growing grain	15-20
Deciduous forest	15-25	Stubble field	15
Evergreen forest	7-15	Concrete	12
Granite	12-15	Asphalt	8
Water	7-10	Urban areas	10-15

5.2 Emissivity

Emissivity is a measure of the degree to which a surface behaves like a perfect long-wave radiator. In principle, a decrease (increase) in surface emissivity would decrease (increase) the long-wave radiative loss from the surface. Because quartz particles have a rather low emissivity, an increase in the area of the world's deserts would therefore reduce the long-wave radiative loss, all other factors remaining unchanged 52.

5.3 The energy balance

Human activities may change the amount of available radiant energy at the Earth's surface as well as the way in which it is partitioned. A quantity that is used in this latter connexion is the Bowen ratio, the ratio of heat losses by convection and by evaporational cooling. The numerical value of this quantity is small over oceans and tropical rain forests, and is large over deserts. Table 5 gives examples of man-made processes that change the Bowen ratio.

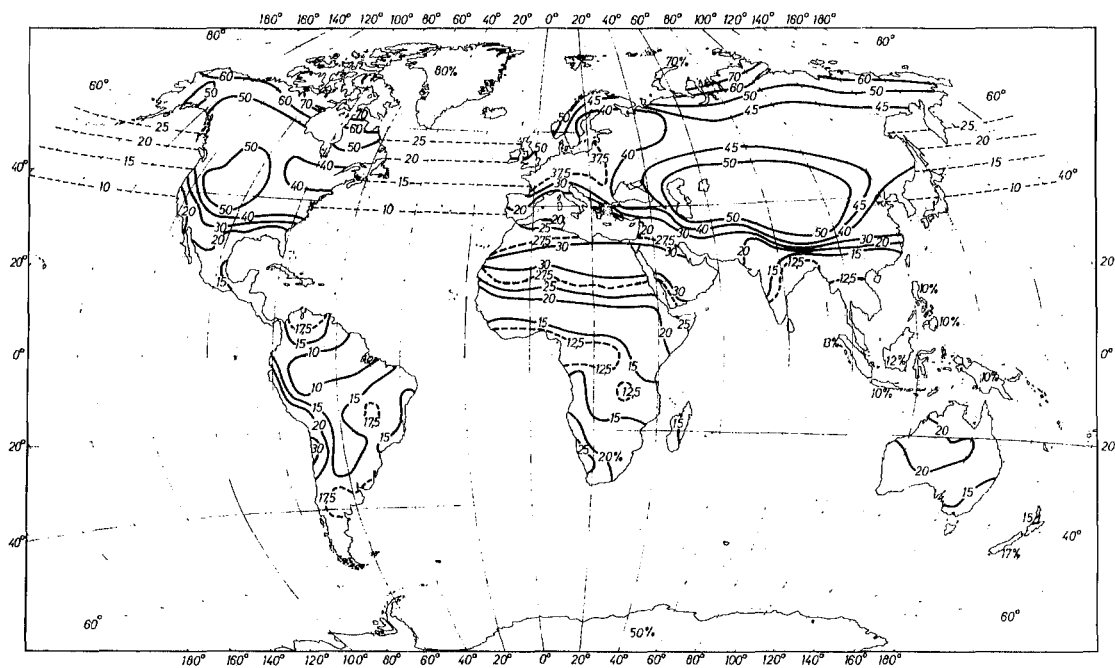


Figure 4a. Global distribution of surface albedo (in %) in January [47].

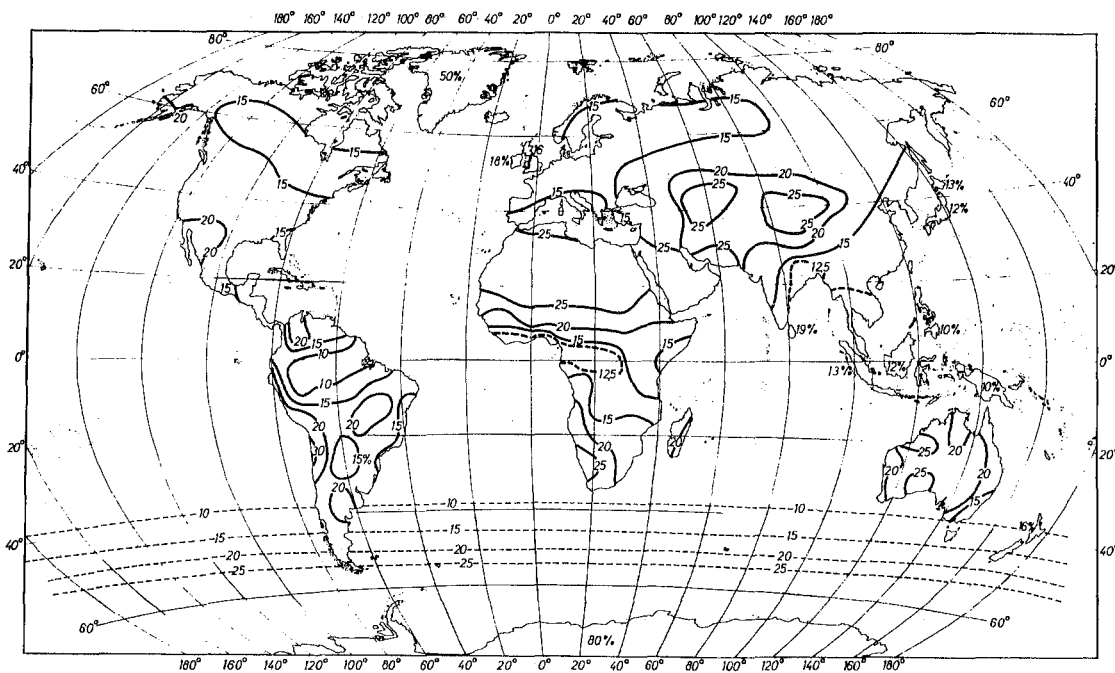


Figure 4b. Global distribution of surface albedo (in %) in July [47].

Table 4

Causes of large-scale changes in land surface albedo

<u>Processes that cause increases in albedo</u>		<u>Processes that cause decreases in albedo</u>	
1.	Desertification	1.	Overgrazing in regions with moderate to heavy rainfall
2.	Overgrazing semi-arid regions	2.	Man-made lakes and irrigation (slight)
3.	Burning of grass-land in semi-arid regions (slight)	3.	Construction of towns (slight)
4.	Ploughing of fields (slight)	4.	Snow removal
5.	Clearing of forests	5.	Deposition of particles on snow
6.	Addition of biological films to water surfaces		

Table 5

Man-made processes that change the Bowen ratio

<u>Processes leading to an increase in Bowen ratio</u>	<u>Processes leading to a decrease in Bowen ratio</u>
Desertification	Irrigation
Clearing of forests	Man-made lakes
Drainage of swamps	Urban growth (in dry climates)
Urban growth (in moist climates)	

Land cultivation may increase or decrease the Bowen ratio, depending upon the type of crop, its stage of growth, climatic region, etc. Locally, a slightly hotter and drier climate results in an increase in Bowen ratio. A decrease in daytime temperatures and increase in humidity reduces the Bowen ratio. These local changes may collectively encompass much of a region.

Mankind has also been changing the thermal properties (conductivity and heat capacity) at the Earth's surface, mostly on the local and urban scales, by constructing roads and buildings, and by ploughing fields. Solar energy is stored during the day and released slowly at night by concrete and cement.

5.4 Surface Geometry

A roof that slopes southward in the northern hemisphere maximizes the amount of solar radiation it receives. Tall buildings in the centre of a city shade the streets and cause the streams of incoming and outgoing radiation to criss-cross from wall to wall. Many other examples of such effects have been described by Geiger [1].

5.5 Surface wind

The surface wind is modified locally by the construction of tall buildings, the clearing or regeneration of forests, and the erection of shelter belts. The surface wind field may also be modified over distances of a few kilometres by differential changes in the surface energy balance, setting the air in motion, e.g., by generating urban wind systems, drainage flows, etc. Although significant locally, these changes are not of large-scale importance.

6. Changes in the hydrologic cycle resulting from human activities

Mankind has been modifying the hydrologic cycle, both inadvertently and deliberately, for a long time. Locally, the most dramatic visual example is the cold-weather ice fog which blankets cities like Edmonton, Canada and Fairbanks, Alaska, and which is caused by moisture released from the combustion of natural gas and from automobile exhausts. Hage [53] found a substantial increase in winter fog-giness in Edmonton between the winters of 1949-50 and 1968-69 due to the growth of the city. In other urban areas, the replacement of vegetation by buildings and roads has the opposite effect, reducing evaporation and increasing run-off, with the result that fog occurs less frequently than in the surrounding countryside. In semi-arid regions, of course, a city may be an irrigated oasis.

Regionally, the hydrologic cycle is modified by forest clearing, forest regeneration, swamp drainage, irrigation projects, dam construction, river diversion, ground-water withdrawal and urban growth. Although of local climatic significance, these changes are sometimes difficult to detect on the larger scale. For example, even at a height of 10 m above a large agricultural area under irrigation, or at a downwind distance of 1 km from a reservoir, the climatic effects may be imperceptible. There may, of course, be a few days per year when relatively small changes in surface conditions are sufficient to trigger or suppress convective cloud activity or shower development although the frequencies may be so small that statistically significant differences are difficult to find. In this connexion, Project METROMEX [54] has revealed a 10 to 30 per cent excess in summer precipitation downwind from St. Louis, Mo., while Schickedanz [55] has found higher rainfall in the vicinity of irrigated regions than in control non-irrigated regions during June, July and August in Kansas, Nebraska and most of Texas: in April, May and September, when irrigation was not practiced, there was no anomaly.

Mankind has also changed the hydrologic cycle over whole continents. The annual evaporation has increased by about 3.5 per cent due to man's activities, although as pointed out by Flohn "the ocean is still the great buffer of the water budget, smoothing man-made variations on land" 50. The increase would have been larger except that desertification and forest clearing result in a reduction of evaporation to the atmosphere. In Latin America, for example, the agricultural land bank is estimated to have increased by 53 and 50 millions of hectares respectively, between 1860-1950 and 1950-1970 55. The effects on the hydrologic cycle and on the general circulation of these changes are still rather uncertain, but there is no doubt that the masses of water vapour involved are substantial.

7. The impact of local and regional changes on global climate

A question of great importance is whether a regional anomaly can affect world climate. This problem can be studied in three ways:

- (a) with numerical simulations;
- (b) by examination of the larger-scale effects of naturally-occurring local and regional anomalies, due for example to the presence of an island or lake;
- (c) by examination of the downwind impacts of a man-made anomaly such as a city or an irrigated area.

As an example of the second approach, the Great Lakes are major sources of heat and water vapour in the winter and are known to affect the motions and intensities of low and high pressure areas moving by. However, the energy involved is about 500 W m^{-2} as compared with 10 W m^{-2} for a megalopolis 50. Another useful analogy is given by the cloud bands sometimes to be seen downwind of tropical islands. When observed on satellite photographs, these clouds resemble the von Karman vortices downwind of a blunt body in a wind tunnel 56, 57. By comparing the energies involved with those proposed for a large industrial power park, an engineering estimate of the likely regional effects might therefore be obtained. The energy releases from various man-made and natural heat sources are given in Table 6 45. Finally, there is the third approach, namely, to make experimental measurements around existing man-made anomalies. For example, the St. Louis urban plume containing heat, moisture and pollutants can sometimes be detected 200 km downwind. Schaeffer 58 has described a case in which snowflurries occurred about 130 km downwind of Buffalo, New York, presumably caused by the urban plume.

In the next decade, there will be many experimental studies of the climatic effects downwind of deserts, forests, cities, and other regional-scale features. There will also be numerical simulations in which the climatic impacts of removing a forest, introducing a heat source, or irrigating a desert will be examined. These two kinds of activities are often undertaken independently by different groups of scientists with different objectives. It is clear that more co-ordination between experimentalists and modellers would be desirable in the planning, the execution and the analysis of the results of such studies. In this connexion, it should be noted that some climatic changes are difficult to reverse. Once a forest is cleared,

for example, soil nutrients may rapidly be leached, and the new temperature and wind regimes may not be conducive to the growth of seedlings.

Table 6

Comparison of man-made and natural energy releases 45

Heat Source	Area (sq. km)	Approximate MW Equivalent Input to the Atmosphere
St. Louis	250	16,100
Chicago	1,800	52,700
One-megaton nuclear device (heat dissipated over 1 hour)		1,000,000
20,000-MW power park	26	40,000
Cyclone (1 cm of rain/day)	10×10^5	100,000,000
Tornado (kinetic energy)	10×10^{-4}	100
Thunderstorm (1 cm of rain/30 min)	100	100,000
Great Lakes snow squall (4 cm of snow/hour)	10,000	10,000,000

There remains the question of providing practical advice on whether major development projects will have significant impacts on climate not only locally but also on surrounding territories. Here it is appropriate to repeat the recommendation made in 1971 by SMIC 44: "We recommend that an international agreement be sought to prevent large-scale (directly affecting over one million square kilometres) experiments in persistent or long-term climate modification until the scientific community reaches a consensus on the consequences of the modification." This recommendation should also apply to land-use changes that may lead to inadvertent and practically irreversible impacts on climate.

As for existing engineering works such as the Aswan Dam, the James Bay power development in Quebec and the diversion of rivers flowing into the Arctic Ocean, climatic impact assessments should be undertaken and the results should be widely promulgated in order to assist in the assessment of similar kinds of proposals in other parts of the world. Some of the assessments are available nationally but they are rarely scrutinized internationally.

8. The carbon dioxide problem

The CO₂ problem merits special attention for several reasons:

- (a) it is global in nature,
- (b) there is unequivocal evidence of increasing atmospheric CO₂;
- (c) much or all of the problem arises from man's use of fossil fuel for energy;

- (d) it may be difficult to alter this source of energy easily or quickly should a change be required;
- (e) numerical models of climate suggest that a doubling in CO₂ will cause warming of the lower atmosphere although the impact will be uneven with some regions possibly experiencing cooling;
- (f) valid predictions of the reality of significant CO₂ impact on climate will be needed in a few decades or less.

8.1 Components of the CO₂ problem

The CO₂ problem has several components, all of which need to be pursued before the implications of increasing CO₂ can be clarified:

- (a) rate of introduction of CO₂ into the atmosphere from fossil fuel combustion;
- (b) rate of deforestation and cultivation of virgin lands;
- (e) modelling of the global biogeochemical cycle of carbon;
- (d) prediction of atmospheric levels of CO₂ for various scenarios of future input of CO₂;
- (e) prediction of climatic changes due to increased atmospheric CO₂;
- (f) analysis of the impact of the climatic change and the enhanced CO₂ on the biosphere and on human activities;
- (g) engineering and socio-economic studies of technological fixes.

8.2 Sources of atmospheric CO₂

8.2.1 Fossil fuel CO₂, 1860 to 1977

The combustion of fossil fuels, the production of cement, and the flaring of natural gas release CO₂ into the atmosphere. The latter two sources are only a few per cent of the first. The fossil fuels include coal, oil, natural gas (mostly methane), and lignite. Information on the consumption of fossil fuels obtained from United Nations Statistical Reports 59 has been used by Keeling 60 and by Rotty 61 to produce the estimates shown in Figure 5. The average growth rate of CO₂ (world fossil fuel energy usage) broken by wars and periods of world economic recessions amounts to between 4 and 5 per cent per annum. It had been expected by some economists that after the recession and energy price rises of 1973-75 the growth rate would slow down to perhaps 2 per cent per annum because of fuel costs and conservation. The reported data indicate no such retardation. Although two years is too short a period of time for trend analysis, there is still no indication in these data that the growth of the world fossil fuel usage is slowing down.

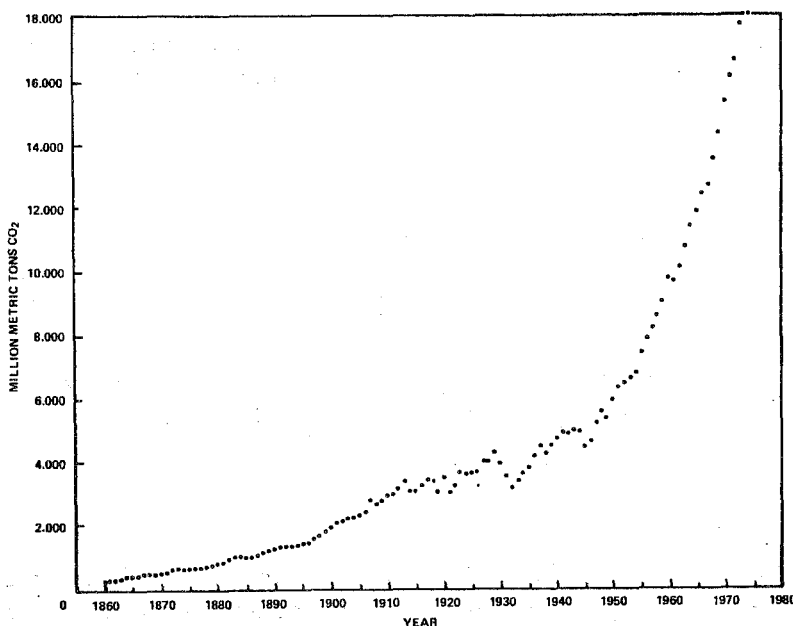


Figure 5. The annual release of carbon dioxide to the atmosphere by the combustion of fossil fuels, cement production and the flaring of natural gas. The last point on the curve gives the 1977 emissions. The 1973-75 levelling-off period was presumably due to price rises in oil and the world economic slowdown [60, 61].

8.2.2 Deforestation

Growing vegetation removes CO₂ from the atmosphere. Globally, the removal rate may be increasing, with many reports that world forests are being cut down by man, [62], but there are only a few reports of deliberate and natural reforestation. Estimates of the effects of deforestation on CO₂ have ranged from virtually zero (or even negative values if the increasing atmospheric CO₂ fertilizes the biosphere) to many times the CO₂ released from fossil fuels during the past 50 to 100 years. Woodwell et al. show some of the estimates in Figure 6 [62]. The techniques for estimating the changes in the biosphere are two-fold; first, through satellite or other aerial monitoring, making a physical estimate of changes over the globe (augmented by ground truth to determine actual changes in carbon) [63]; second, using changes in atmospheric content of the isotopic carbon [64] or the change in oxygen concentration of the atmosphere [65]. Neither method is easy and neither necessarily guarantees a successful result. Even after much research and effort, the global biosphere contribution to atmospheric CO₂ may still be unknown.

Deforestation is mainly a phenomenon of the developing countries today whereas fossil fuel emissions are concentrated in the industrialized countries. Figure 7 displays the proportions of fossil fuel CO₂ released into the atmosphere in 1974 in broad categories of countries [66]. For example, the United States with less than 10 per cent of

the world population emits over 25 per cent of the world fossil fuel CO₂. On the other hand, the developing countries release less than 15 per cent.

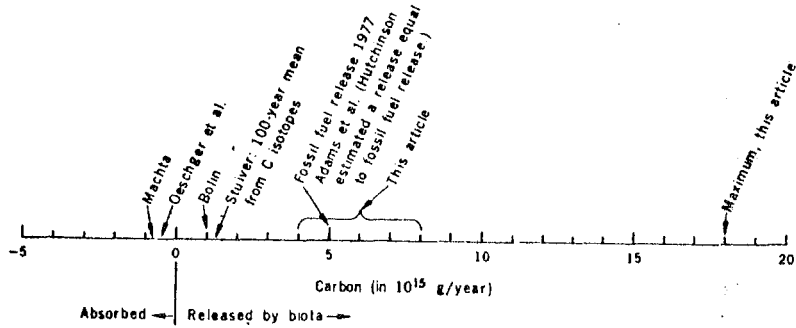


Figure 6. Estimates of the annual release of carbon in the form of CO₂ from the world's biota, including humus. Sources quoted will be found in 62, and include 64, 71. See also Overview Paper by Bolin.

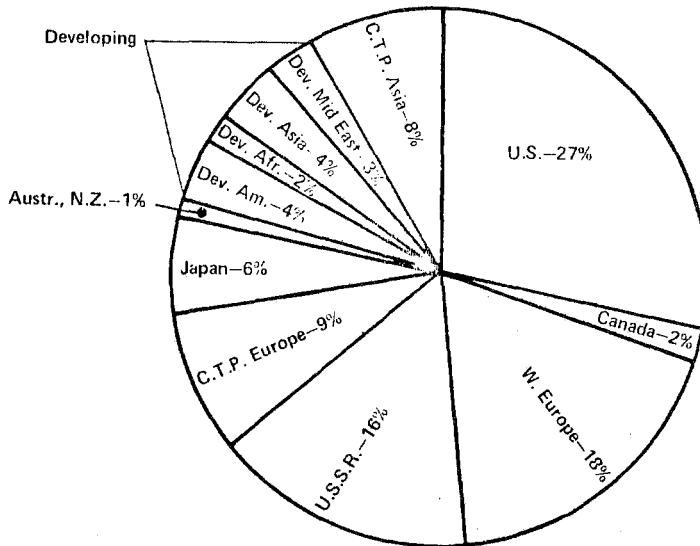


Figure 7. Geographical distribution of CO₂ production in 1974 66.

8.3 Predictions of future fossil fuel sources of energy

Estimates of the total recoverable fossil fuels are uncertain. In large part, this is due to the possibilities of new technology for economic recovery of oil shales, tars, etc., and unexpected major new fossil fuel discoveries. Most present estimates of recoverable fossil fuels expressed in equivalent carbon content are close to $5 - 10 \times 10^{13}$ g carbon.

It should be noted that coal produces more CO₂ than does oil or natural gas for the same energy production: 87, 71 and 51 metric tons, respectively, per 10^{12} joules for coal, oil and gas. Since in the long term it is almost certain that fossil fuel energy, if it is used, will favour coal in increasing proportions (85 per cent of the known recoverable fossil fuel energy is in coal), the CO₂ released to the atmosphere will be greater than the present mix even with the same energy production.

The range of predictions of energy consumption and the proportion of the energy contributed by fossil fuels is large. Williams *et al.* offer two possible scenarios in their overview paper at this Conference. The 35 Terrawatt nuclear and solar scenario virtually eliminates fossil fuel early in the next century. The 50 Terrawatt fossil fuel scenario places complete reliance on coal after about 50 years. Figure 8 presents future energy scenarios for the U.S.A., proposed as possibilities by Lovins [67], one of which also reduces or eliminates dependence on fossil fuels. While there are yet many other uncertainties in the CO₂ problem, it is evident that should the world greatly reduce or avoid its dependence upon fossil fuels, and also wood from deforestation, the CO₂ problem would disappear.

Finally, Figure 9 portrays one estimate of the geographical distribution of the sources of CO₂ in 2025 AD, the counterpart of Figure 7 which described actual conditions in 1974 [66]. The small circle for 1974, in fact is drawn to scale compared to that for 2025. While this prediction [66] cannot be accepted uncritically, it is suggestive that the largest future growth in CO₂ releases are likely to be in the developing countries. This provides another argument for global interest in the CO₂ problem.

8.3.1 Predictions of future biospheric CO₂

If deforestation has been significant compared to fossil fuel sources or even if it is now relatively small, the trend in the near future may be towards increasing rates of deforestation. This is likely because of increasing population, rising fuel costs, and economic growth based on forest products.

8.3.2 Future fossil fuel releases used in calculations

A mathematical function, called a logistic function, is often used to describe the year by year releases of CO₂. The function is given by:

$$R(t) = r \left[1 - (N/N_{\infty})^n \right]$$

where $R(t)$ is the annual amount of CO₂ (or carbon in CO₂) released to the air, r is a constant chosen to provide the desired value of $R(t)$ for the first year of the

prediction, N is the accumulated amount of CO_2 (or carbon in CO_2), N_{∞} is the total amount of CO_2 (or carbon in CO_2) which can be used and n is a growth cutoff factor. Figure 10 presents a graph of various values of n [68]. Each curve in the figure contains the same total amount of fossil fuel CO_2 , N_{∞} , but as n becomes larger the fossil fuels are consumed faster. The figure also indicates why a logistic function has been used. The world is thought to consume fossil fuels at an increasing annual rate until the reserves become progressively more difficult to extract. The usage rate will then decrease until all the fossil fuels are consumed.

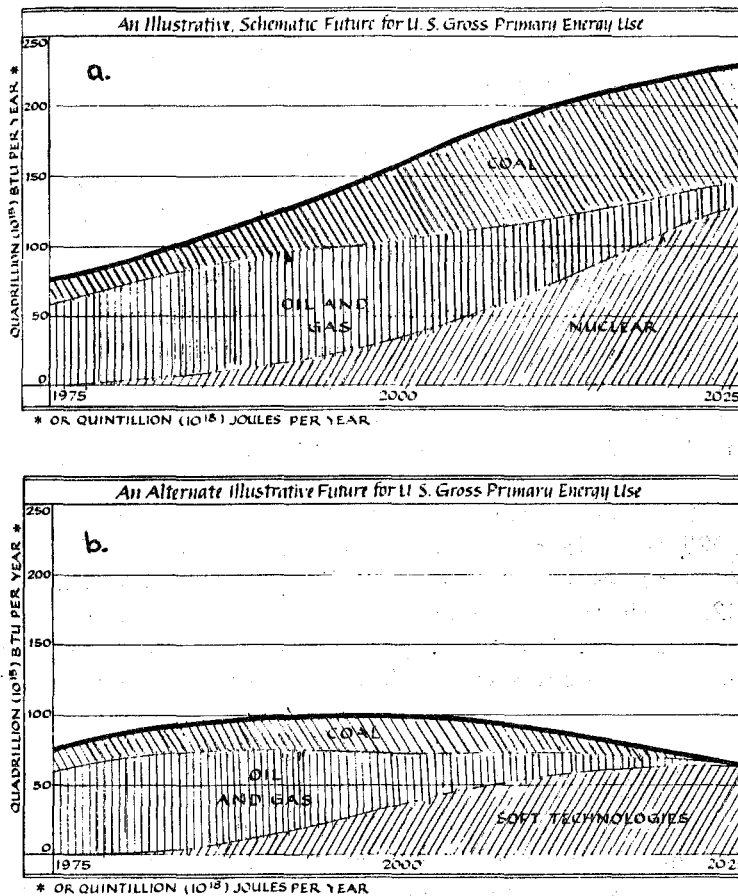


Figure 8. Two possible scenarios for future U.S. energy production and use [67]. Lovins refers to (a) as the "hard energy path", and to (b) as the "soft energy path" with less energy demand.

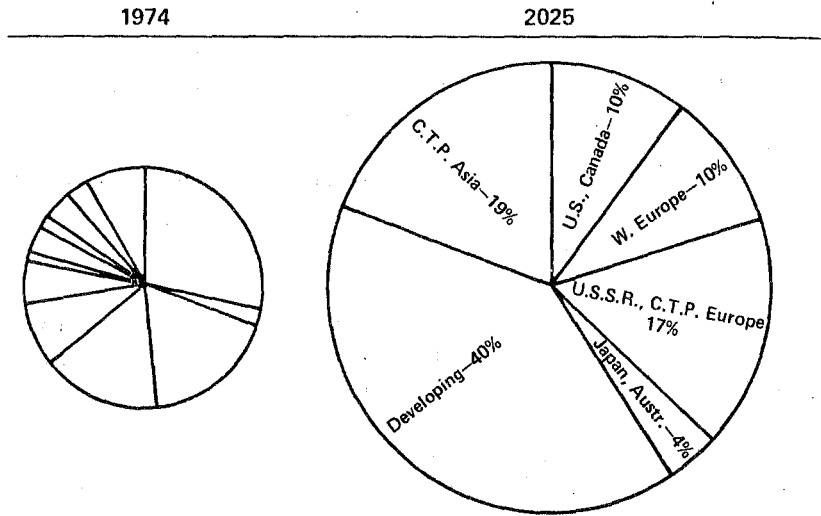


Figure 9. Geographical distribution of CO₂ production in 1974 and estimates for 2025 66. Relative areas of circles indicates total amount produced.

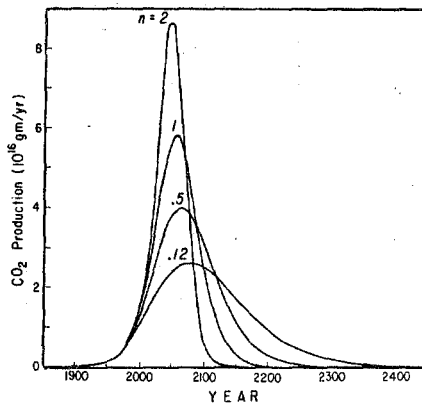


Figure 10. CO₂ production for various values of the parameter n in the logistic function 68. In this case N_{∞} is 8.2 times the amount of carbon in preindustrial atmospheric CO₂.

8.3.3 Prediction of future atmospheric concentrations of CO₂

Predictions of future atmospheric CO₂ due to man's activities are obtained through an application of our understanding of the carbon cycle, i.e., the exchanges of carbon and its compounds in nature. Reservoirs of carbon which possess carbon lifetimes measured in many thousands of years or more are neglected (unless man's disturbances shorten the lifetime) as are reservoirs which are very small. Unfortunately, in many cases, the exchange rates and reservoir sizes are known imperfectly; this ignorance is often used, unwisely, as an excuse for neglecting them.

Figure 11 illustrates one of the simpler models simulating the reservoirs and exchanges of carbon. Note that there are three major reservoirs; the atmosphere, the biosphere and the oceans; and furthermore that each of the three major reservoirs is further subdivided - the atmosphere into a troposphere and stratosphere, the oceans into an upper mixed layer and a deep ocean layer, and the biosphere into short and long lived biota. In this kind of model, information on size and transfer rates are often lacking or poorly known.

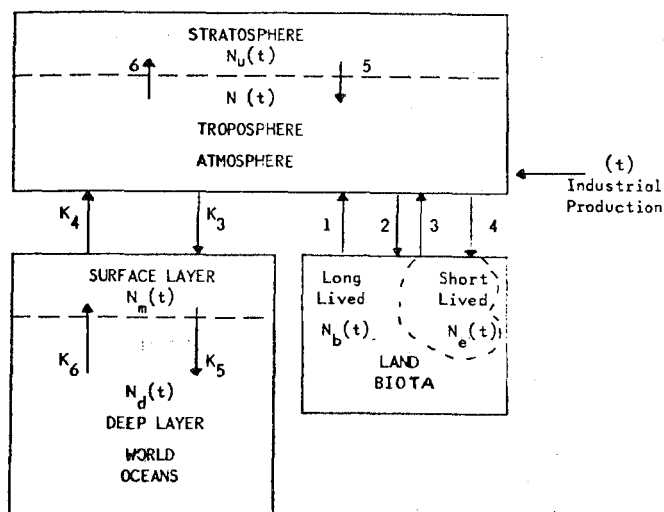


Figure 11. A model of the various exchangeable carbon reservoirs in a predictive model of future levels of atmospheric carbon dioxide. The meaning and values of the symbols may be found in the paper by Keeling and Bacastow 68.

8.4 Past atmospheric growth of CO₂

The best established feature of the CO₂ problem is the growth in atmospheric concentrations. The measurements over the past 20 years at Mauna Loa, Hawaii (3 400 m altitude) in Figure 12 display a general upward trend 68, 69. This growth has been observed at other places such as Point Barrow, Alaska (73°N), the South Pole, and in the middle atmosphere as measured from aircraft by the University of Stockholm. For all practical purposes, each of the clean air locations, and even some places near cities, display virtually the same long-term growth rates.

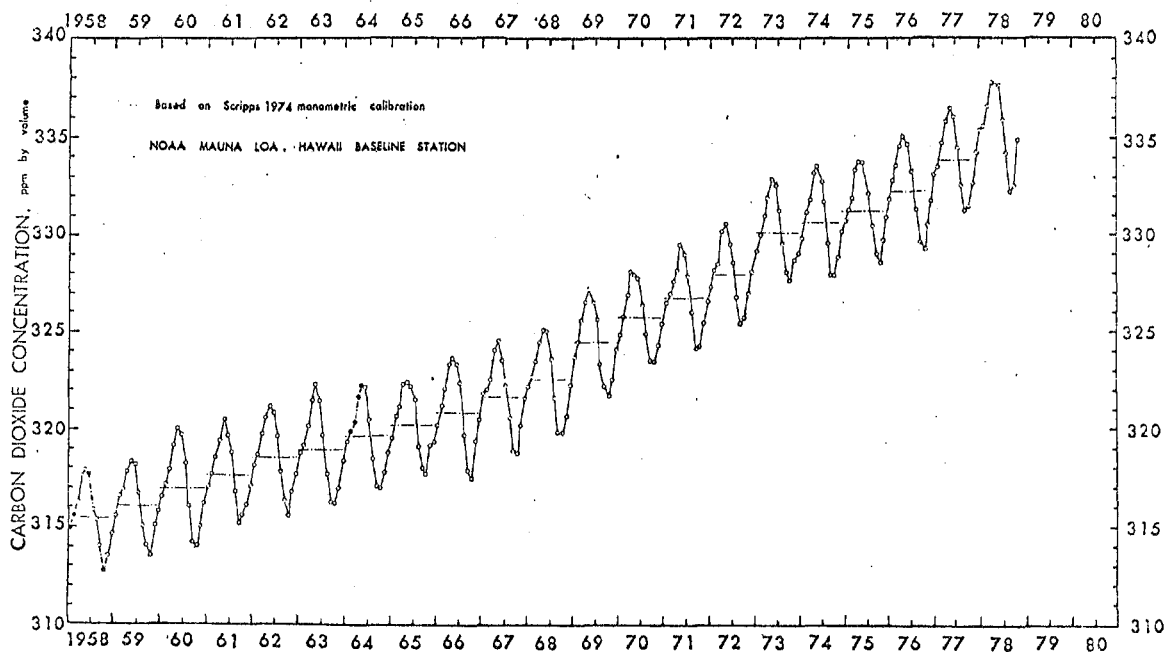


Figure 12. The mean monthly atmospheric carbon dioxide concentrations at Mauna Loa, Hawaii (19°N , 3 400 m altitude) 68, 69. Dashed horizontal lines are average calendar year concentrations.

The seasonal cycle which is also very conspicuous in Figure 12 is due to the uptake of CO_2 during photosynthesis and its return to the air when the organic matter rots or otherwise oxidizes. The change in amplitude of the seasonal variation with latitude offers interesting analysis possibilities 70.

For the 20-year period from 1958 to 1977, one can estimate the increase in atmospheric CO_2 from actual observations such as those in Figure 12. The increase amounts to slightly over one-half of the amount of CO_2 added to the atmosphere by fossil fuel combustion. This 55 per cent airborne fraction of fossil fuel CO_2 input to the air has been used to calibrate the rates of exchange in many of the carbon cycle models; the bulk or all of the remaining 45 per cent is presumably taken up by the world oceans. If deforestation is contributing a significant additional amount of CO_2 to the air, then this would also have to be put in the oceans.

8.5 Box model simulations

As an example of a recent simulation of future levels of atmospheric CO_2 , Keeling and Bacastow used the logistic function of Figure 10 in the box model shown in Figure 11. A number of their results (Figure 13) deserve comment:

- (a) The model assumptions lead to a doubling of pre-industrial atmospheric CO_2 concentrations sometime in the early to mid-part of the next century.

- (b) The long-term decline of elevated concentrations to pre-industrial levels would take many centuries because of the slow interchange between surface and deep ocean waters.
- (c) Viewed in a very broad long-term perspective, it does not make much difference which of several scenarios on energy consumption is used in the calculations; the timing and peak concentrations are not very different.

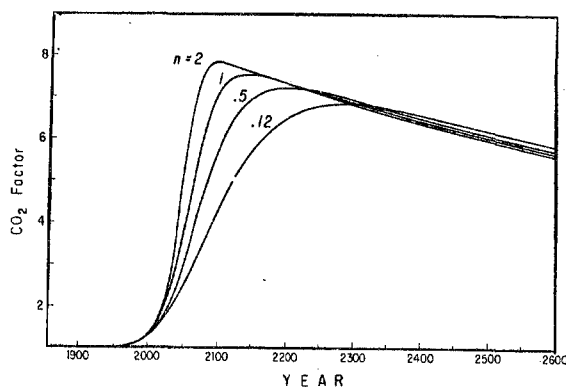


Figure 13. Increase in atmospheric CO₂ estimated using the production rates shown in Figure 10 and the box model of sources and sinks shown in Figure 11 [68].

Siegenthaler and Oeschger [71] have formulated a model of the carbon cycle in which the exchange between the mixed layer of the ocean proceeds with and through the deep ocean via diffusion. The transfer still remains one-dimensional, i.e., only in the vertical. For CO₂ inputs into the atmosphere similar to those of Keeling and Bacastow, the box-diffusion model yields substantially the same results. Siegenthaler and Oeschger have used their model in the following way. If the limit of allowable concentration were to be set at 50 per cent above the pre-industrial level of 300 ppmv (e.g., 450 ppmv), the resulting world-emission rate could be estimated from their model. Thus if sufficient information about all components of the CO₂ problem becomes available and if continued release proves to be objectionable, it may be possible to estimate acceptable or allowable world use of fossil fuels (and/or deforestation) using the Siegenthaler-Oeschger modelling approach.

8.5.1 Status of present CO₂ models

New doubts about carbon cycle models have arisen in the last several years because of a realization that there are potentially large past and current sources of biospheric CO₂. Calibration of the models via an airborne fraction is therefore not possible. Second, models of oceanic exchange between surface thermocline and deep waters have not been validated by long-term tracer studies. To follow transient oceanic tracers for a decade or two is inadequate when the postulated exchange times

are measured in hundreds of years or more. The role of biospheric transfer (e.g., settling of fecal pellets), the dissolution of carbonates, and the special role of estuaries, large lakes and coastal waters raise further speculations. Thus, it cannot be said that carbon cycle modelling is on a firm footing.

8.6 Predicting climatic changes due to increasing CO₂

The quantitative basis for predicting future climates from a modification of atmospheric properties has been the subject of several of the papers of this Conference. Here it seems appropriate to emphasize those aspects unique to the CO₂ problem.

The growth of atmospheric CO₂ is assumed to be relatively gradual. Thus far, the calculations have treated two discrete cases; one with pre-industrial CO₂ concentrations and a second with a larger amount, usually twice the first. Each is assumed to be in steady state. Ultimately, it will be necessary to perform calculations simulating the transient intermediate state to test whether the atmosphere behaves differently at such times.

The computations of climatic change assume that the entire atmosphere contains the same CO₂ concentrations (by mass or volume). This assumption appears to be justified.

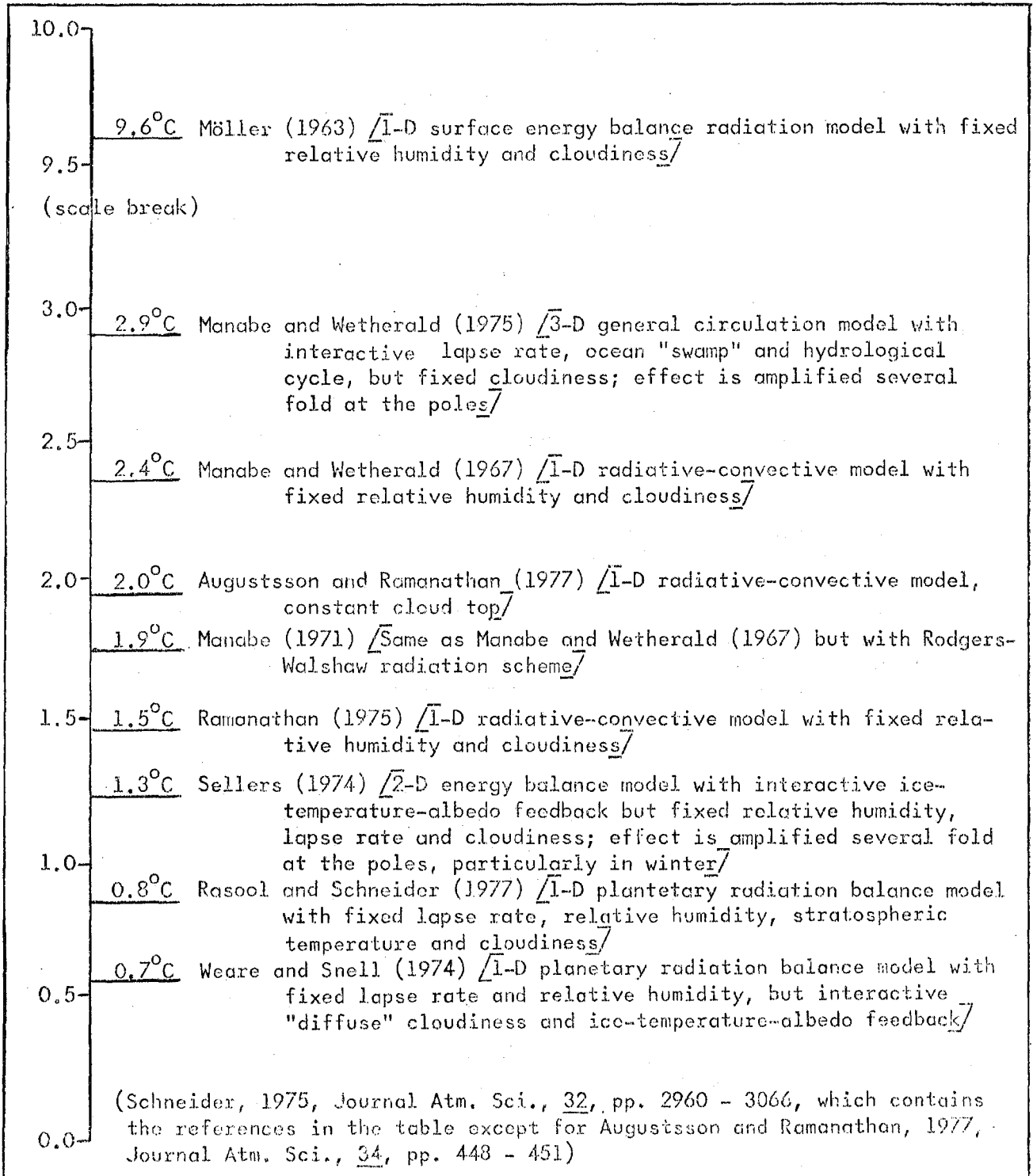
The biospheric carbon production is dependent on atmospheric CO₂, higher concentrations of atmospheric CO₂ increasing the rate of photosynthesis.

A number of investigators have examined the CO₂ effects on the heat balance by one-dimensional (vertical direction only) climate models [72, 73]. Only the paper by Manabe and Wetherald [74] uses a three-dimensional model. Despite the range of complexity, the estimates of global warming have been surprisingly similar, as shown in Table 7. It is likely that even more realistic simulations would not modify the likely order of magnitude of the expected global temperature changes.

But this optimistic assessment (which remains to be proven) must be tempered by the need for more than global temperature changes. More particularly, other climatic parameters, especially precipitation, and regional or smaller-scale differences are necessary to evaluate environmental impacts. To date, the three-dimensional model of Manabe and Wetherald only hints at a few of the kinds of regional climatic changes one might expect. For example, in their simulation, the polar front was shifted poleward when CO₂ concentrations were doubled. This would imply less frontal precipitation in areas from which the polar front had moved. The retreat of the snow-line in northern arctic regions fed back to an even greater warmth since the albedo dropped markedly. This positive feedback was augmented by the low-level stability of the winter arctic. The result was a northern hemisphere high-latitude low-level temperature increase of as much as 10 deg C whereas average global warming in the same computer runs was less than 3 deg C.

Table 7

Surface temperature responses to a doubling of CO₂ to 600 ppm



There has been some effort to study regional conditions during past periods of warm climate [27, 72]. There is no doubt that this approach should be pursued, but in itself it will not necessarily be convincing. One invariably asks whether the conditions during an earlier warm period would necessarily repeat themselves with a new warming due to the greenhouse process.

There are tremendous difficulties in simulating climate with sufficient fidelity to be confident in a forecast of climate changes due to increased CO₂. It may well be that within 5 or 10 years, governments could come to a crossroad on long-term future energy and land-use policies, and even then the climate simulations may still leave much to be desired.

8.7 Environmental impacts of global warming and increased CO₂

Some of the environmental impacts which, one speculates, may result from greenhouse warming are:

- (a) Altered precipitation and evaporation regimes. Although the locations cannot be forecast, it is very likely that there will be regional differences and that some areas may show a decrease in precipitation even if (as is expected) the global average increases.
- (b) Recession of snow-lines and recession or even disappearance of mid-latitude glaciers.
- (c) Except for the possibility that the warming might develop some dynamic instability in the West Antarctic ice cap [75] most meteorologists do not foresee rapid land-ice melting and consequent sea-level rise. The year-round absence of arctic sea ice remains a possibility and this may produce secondary climatic effects (such as more snow) especially in neighbouring arctic land masses.
- (d) Warming of arctic surface waters could disturb the oceanic circulation with consequent reduction in the upwelling process. The upwelling waters are important to fisheries.

8.7.1 Benefits from an increase in atmospheric CO₂

There is laboratory evidence that with adequate nutrients, water, and sunlight, photosynthesis and hence agriculture and forest productivity will increase with increasing atmospheric CO₂ concentrations. The benefits to agriculture and forestry vary from species to species and, in some cases, may be negligible. More importantly, a CO₂-induced climatic change need not necessarily be unfavourable.

8.7.2 Engineering technological fixes

Should research demonstrate a high likelihood that fossil fuels and deforestation will produce serious environmental threats, the world has a number of choices.

- (a) Substitute alternate energy sources for fossil fuels. The lead time for such a transition will be many decades; each alternative must itself be examined for potential environmental impacts.
- (b) Removal of CO₂ from major sources or from the air itself by chemical and cryogenic methods. The CO₂ must then be stored. The energy demands for removal may exceed the amount of energy derived from the burning of fossil fuels 76.
- (c) Increase the mass of the biosphere by planting more trees. For projected CO₂ growth, the number of trees to be planted is prohibitive; when cut, the wood must be sequestered in "permanent" non-exchangeable reservoirs 76.
- (d) Accelerate oceanic uptake by fertilizing the oceans.
- (e) Counteract climate changes by another form of human interference. The addition of dust or aerosols over the oceans has been suggested. Also, one might reduce the atmospheric content of another greenhouse gas with a much smaller content which might be easier to remove 77. Alternatively, the net radiative balance with increased CO₂ might also be returned to pre-industrial values by increasing the ground albedo.

The first proposal, to use a source of energy other than fossil fuels, presents the world with a potentially difficult and costly problem. The other suggestions are speculative; in most cases the engineering feasibility has not been fully thought out. There is therefore a sense of urgency in determining whether there is likely to be any real environmental or socio-economic threat from growing atmospheric CO₂.

8.8 A resumé of opposing views about the CO₂ problem

Many scientists believe that: "The continued fossil fuel usage (and possibly deforestation) presents a potential threat to the environment". However, there are many uncertainties in the scenarios, and arguments have been advanced to suggest that the CO₂ problem may have been exaggerated.

- (a) The world surface temperature has been cooling since 1950 while the CO₂ has been growing fastest; does not this cast doubt on greenhouse warming of the atmosphere?
- (b) If deforestation has been significant, the sink of CO₂ in the oceans (or elsewhere) must actually be much greater than present models admit; are the predictions of future CO₂ concentrations much too high?
- (c) Nature can take up the extra fossil fuel CO₂; the forests will grow faster; when the arctic ice melts, the oceans will be able to absorb more CO₂.

- (d) The atmosphere is resilient. The presumed stability of the climate for the past thousands of years argues that perhaps negative feedback mechanisms can adequately cope with the greenhouse warming; for example, a small increase in low cloudiness over the world can balance a sizeable increase in CO₂.
- (e) There are predictions for naturally-occurring cooling trends during the next few decades; the CO₂ greenhouse warming would then be welcome.
- (f) The environmental effects will be gradual and man can easily adjust to the changes.
- (g) Atmospheric warming may be advantageous to many areas and only marginally worse to others; for example, sub-polar countries might welcome a warmer climate.
- (h) At worst, man can remove the CO₂ from the air; alternatively, man can undertake technological fixes to prevent or reverse the climatic effects.

Some of these arguments may suggest that climate predictions are still too uncertain to provide a basis for making recommendations about energy policies. However, there is still a sense of urgency connected with the task of studying CO₂ impacts on climate and thus on society. The development of an integrated global research strategy would be a useful forward step in this direction.

9. Conclusion

There is ample evidence that local and regional climate can be modified by mankind. In addition, the chemical composition of the atmosphere is changing on the local, regional and global scales due to human activities (e.g., concentrations of CO₂ and chlorofluoromethanes are increasing). There is, however, no experimental evidence to demonstrate that global climate has been affected by human activities, although modifications might conceivably exist, remaining undetected because of the great natural variability of climate.

Of the various mechanisms that could affect global climate, the greenhouse problem should be given the highest priority in national and international research and planning activities. In essence:

- (a) The best current estimate argues that there is a potential problem of warming of the lower atmosphere due to increasing concentration of the greenhouse gases.
- (b) There are, however, outstanding uncertainties in simulations of future atmospheric concentrations and of the resulting impacts on climate.
- (c) Few predictions call for significant climatic effects before 2000 AD.

- (d) Research may be able to resolve many of the uncertainties.
- (e) There are doubts about the significance of the greenhouse problem over and above the uncertainties.
- (f) There are no currently known feasible alternatives to reduction in the release of CO₂ should the CO₂ problem prove to be real and the impact unacceptable.
- (g) Few, if any, scientists believe the CO₂ problem in itself justifies a curb, today, in the usage of fossil fuels or deforestation.
- (h) Studies of the climatic impacts of an increase in the concentrations of greenhouse gases, and of the resulting impacts on society, should be pursued internationally with great vigour. In these studies, joint climatic impacts, including, for example, those due to regional changes in albedo, Bowen ratio and particulate concentrations, should be given high priority.

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SOME RESULTS OF CLIMATE EXPERIMENTS WITH
NUMERICAL MODELS

B.J. Mason*

1. Introduction

Climate is the synthesis of weather over a period long enough to establish its statistical characteristics (mean values, variances, probabilities of extreme events etc.) and climate prediction is concerned with how the statistics will change in the future.

Although the processes involved in the maintenance of the Earth's present climate are broadly known, those responsible for climatic fluctuations are largely unknown. Climatic changes involve not only the atmosphere but also the world's oceans, ice masses, the global land surface and its biomass. The complete climatic system therefore embraces the atmosphere, hydrosphere, cryosphere and the Earth's surface and all the interactions which occur among them over a wide spectrum of space and time scales. In addition the whole climatic system is subject to external influences, notably the incoming solar radiation and, increasingly, to man's activities.

Predictions of the extent and duration of climatic changes are not possible at present and must await greater knowledge and understanding of the underlying causes whether internal or external to the atmosphere. The first priority is to understand the physical basis of the presently observed climate which requires the development of numerical models to represent the essential climatic processes and interactions.

Fairly simple models which ignore or grossly simplify some parts of the problem can be used to explore specific aspects. For example, one-dimensional models, treating the atmosphere as a single vertical column, may be used to give some insight into the globally-averaged effects of radiative heat transfer but can make little allowance for the influence of atmospheric motions and provide no information on the geographical distribution of climatic parameters. Two-dimensional models which assume that the complex atmospheric motions can be represented crudely by averages over latitude bands, are generally more realistic than one-dimensional models and provide powerful test beds for exploring new formulations and parameterizations but they

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performer fail to represent and reproduce many important features of the observed world's climate especially those that are strongly influenced by regional, geographical and topographical features, such as the monsoons. Examples of the limitations of grossly simplified models are given later.

2. Description and properties of global circulation - climate models

By far the most promising approach to the simulation and understanding of the present global climate lies in the development of fully three-dimensional numerical models which treat the atmosphere as a vast, turbulent, rotating fluid heated by the sun and exchanging heat, moisture and momentum with the underlying continents and oceans, and which allow for monthly and seasonal changes in solar radiation, ocean-surface temperatures, ice cover etc. These general circulation models (GCMs) are based on the physical principles governing the changes in mass, momentum, energy and water substance, on the Newtonian (Navier-Stokes) equations of motion applied to a parcel of air, the laws of thermodynamics, and the equation of state of a gas (air). The governing equations are as follows.

Equations (1) and (2). Two equations describing the horizontal motions of the air in which the time rates-of-change of the E-W and N-S components of the wind are related to the forces exerted on the air by the rotation of the Earth, by horizontal pressure gradients, and by retarding forces such as friction and turbulent dissipation of energy.

Equation (3). A similar equation describing the vertical motion of the air under the influence of forces that arise from gravity, vertical pressure gradients, rotation of the Earth, and from frictional and turbulent stresses.

Equation (4). An equation of continuity which relates changes in the density and velocity of the air in such a way that mass is everywhere conserved.

Equation (5). A thermodynamic equation which relates the supply of heat by radiative and convective processes to a parcel of air to the resultant changes of temperature and pressure.

Equation (6). An equation of state connecting the pressure, density and temperature of the air.

Equation (7). An equation representing the evaporation, condensation and precipitation of moisture while conserving the total mass of the water substance, the heating term in Eq. (5) being modified to include the supply of latent heat.

This set of seven differential equations involves seven dependent variables: the three components of the wind, the pressure, density, temperature and humidity of the air, all expressed as functions of space and time. In practice the meteorologist measures the horizontal winds, the atmospheric pressure, temperature and humidity, near the Earth's surface and in the upper air.

The vertical component of the air motion on large horizontal scales is too small to be measured directly. Indeed, motion on these scales may be regarded as quasi-two-dimensional, and predominantly in horizontal surfaces. The third equation

of motion is, in consequence, degenerate and, since vertical accelerations may be neglected, reduces to the hydrostatic equation relating the pressure difference between two points in the vertical to the static weight of air between them. It is often then convenient to use pressure as the vertical variable rather than height; the density ceases to appear in the equations and the continuity equation is similar to that of an incompressible fluid. In pressure co-ordinates, the analogue of the vertical velocity is the individual rate of change of pressure. It can be calculated by integrating the horizontal velocity divergence with respect to pressure in the vertical, assuming a zero value at the top of the atmosphere. The primary variables in the equations are then the horizontal components of velocity, the temperature and the mixing ratio for water vapour. The vertical velocity is derived from the horizontal motion, while secondary quantities such as the amount of precipitated water substance can be deduced from the primary variables.

Having specified the boundary conditions, and starting from a given initial situation as represented by initial values of all the variables at a network of discrete points filling the whole of the atmosphere, or from a motionless, isothermal, dry atmosphere of specified mass and composition, the governing set of differential equations may be integrated forward in short time steps for periods of months or even years without the model becoming meteorologically or computationally unstable. In an initially isothermal atmosphere, differential heating by the sun produces pressure gradients and consequently air motions. As the integration proceeds, typically on a spherical grid with horizontal resolution of a few hundred kilometres and 5 to 10 levels in the vertical, the wind gradually strengthens until transient large eddies closely similar to the cyclones and anti-cyclones of the real atmosphere are generated. These redistribute the heat and moisture and the model, after some 50 days, reaches a state of statistical equilibrium and produces quantities which, when averaged over a month, reproduce quite realistically the distributions of temperature, pressure, wind and rainfall observed in the real atmosphere. By changing the boundary or external conditions (e.g., solar input and sea-surface temperatures) month by month, the seasonal changes are also well simulated.

Sophisticated global circulation models (GCMs) constructed on these basic principles have been developed and tested by several groups in the United States, notably by the Geophysical Fluid Dynamics Laboratory, Princeton (GFDL), the Goddard Institute of Space Science (GISS) and the National Center for Atmospheric Research, Boulder (NCAR), and in the United Kingdom by the Meteorological Office (Met.O.). These models, although having much in common, differ considerably in their mathematical techniques and hence in computational efficiency and, more importantly, in their specification of boundary conditions and in the representation of physical processes, especially of those which occur on scales too small to be resolved by the models but whose overall contribution to transport and energy-conversion processes must be represented if only statistically in terms of larger-scale parameters. Because these processes, such as turbulence and small-scale convection, cannot be represented explicitly by the model equations there is no such thing as a unique, completely deterministic climate model.

Since the purpose of this paper is not to describe and compare the various models in detail, but rather to present some important results of model simulations and tests of the sensitivity of model climates to some possible natural and man-made perturbations, I shall draw mainly on models developed at the GFDL, Princeton, and at

the Meteorological Office. They have been used in a wide variety of climate investigations and their results, which have been analysed in considerable detail, appear to be as realistic as any that have been produced. Table 1 lists the typical characteristics of the models whose results are mainly described in this paper. The details of the GFDL model are given by Holloway and Manabe [1], those of the Met.O. 5-level model by Corby et al. [2, 4], Gilchrist et al. [3] and those of the Met.O. 11-level model by Saker [5].

Table 1
Characteristics of GFDL and Met.O. Models

	GFDL	Met.O.
Total number of levels	11	11 5
Levels in boundary layer	3	3 1
Levels in stratosphere	4	3 1
Top level (mb)	10	20 100
Horizontal resolution (km)	250	220 330
Insolation specified by	season and latitude	season, latitude and diurnal
Absorbing gases	H ₂ O, CO ₂ , O ₃	H ₂ O, CO ₂ , O ₃
Cloudiness	values at 3 levels	implicit or fixed at 1 or 3 levels
Sea-surface temperatures	climatological prescribed monthly	climatological monthly seasonally
Snow cover	computed	computed albedo only
Sea ice	computed	specified
Soil moisture	computed	computed fixed
Land albedo	fixed	zonal mean values
Land surface temperature	computed with no storage	computed with storage

In both 11-level models the solar radiation at the top of the atmosphere is specified as a function of season and latitude; the UK model also includes diurnal variations. The Earth's topography is prescribed and the temperatures of the land surfaces are determined by solving the relevant heat balance equation using prescribed values for the surface albedo. Changes in soil moisture and snow depth are computed as differences between precipitation (rain/snow), run-off and evaporation. The GFDL

model calculates changes in sea-ice cover but the Met.O. model keeps this fixed. Sea surface temperatures are held at their observed monthly/seasonal values.

In the GFDL model an observed mean distribution of high-, medium- and low-level clouds, varying with latitude but not longitude, is used to compute the transfer of solar and terrestrial radiation between levels. In the Met.O. models the cloud is either implicit or, in some experiments, fixed at one or three levels. In both models the radiation calculations involve three absorbing gases - carbon dioxide, water vapour and ozone. The mixing ratio of carbon dioxide is assumed to be constant everywhere. The distribution of water vapour is calculated step-by-step in the model but the variations of ozone with season, latitude and height are specified by average observed values.

The fluxes of momentum, heat and water vapour at the Earth's surface are calculated in terms of the surface roughness, atmospheric stability, the wind at the lowest level and the gradients of potential temperature and humidity mixing-ratio between the lowest level and the surface. In the absence of buoyant convection the vertical turbulent diffusion of all three quantities through the lowest three layers of the model is computed in terms of their vertical gradients, the variation of wind with height and the stability. If the lowest layers are convectively unstable, heat and moisture are assumed to be transferred entirely by a simple convective mechanism but momentum is transferred by turbulent diffusion.

The convective transfer of heat and water vapour, both in the surface boundary layer and in the free atmosphere, is represented by the exchange and mixing of air between layers as the result of a simple overturning process which continually modifies the vertical temperature and humidity gradients. The hydrological cycle is simplified to the extent that condensation is assumed to occur when the relative humidity of the air exceeds 100 per cent and the excess moisture is deemed to fall out as rain or snow, allowance being made for evaporation if the precipitation subsequently falls through unsaturated air. The dynamical effects resulting from the large-scale release of latent heat of condensation are automatically computed but the effects of small-scale convective motions are represented only by rather crude statistical averaging with some allowance for mixing between the rising, moist air and the cooler, drier surroundings.

A serious weakness of both models is that the type and amount of cloud (as distinct from precipitation) are not computed so the important interactions between the clouds and the radiation field are not accurately represented although the effects of the observed average cloud cover on the radiation budgets are allowed for. Clouds account for nearly two-thirds of the planetary albedo and participate in several important feed-back mechanisms that regulate the temperature. Changes of about 5 per cent in cloud amounts and about 500 m in cloud height may produce changes of 3-5 deg C in surface air temperatures.

A second major deficiency of the models is that they fail to represent interactions between the atmosphere and the oceans which, because they store and transport great quantities of heat, almost certainly exert a strong long-term control on the climate. Models of the ocean circulation are still in an early stage of development, not least because ocean currents, turbulence, temperatures and salinities

are not extensively and continually measured. Although one or two simplified oceanic GCMs have been provisionally coupled to atmospheric GCMs, none has taken full account of the effects of the oceanic surface mixed layer, the presence of meso-scale eddies which are thought to dominate transport and mixing processes in the oceans, and the formation of sea ice. The development of coupled atmosphere-ocean, cryosphere models which would predict rather than prescribe the sea-surface temperatures and their changes, would appear essential to a full understanding of the global climate and the ultimate prediction of climatic changes.

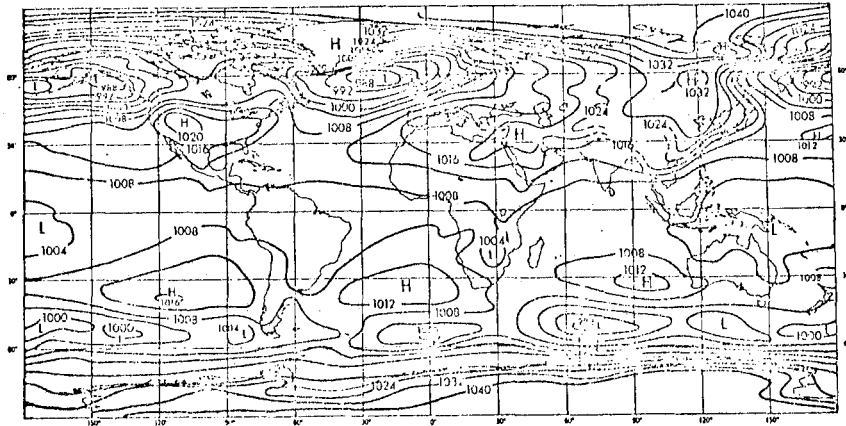
3. Model simulation of the present global climate

Nevertheless, and despite these deficiencies, the best of the GCMs successfully simulate the major features of the global atmospheric circulation and of the present world climate, at least as far as the averaged conditions are concerned. In particular they have been remarkably successful in simulating:

- (a) the presently observed global patterns of surface pressure, wind, temperature and rainfall and their seasonal changes;
- (b) the various components of the global heat, momentum and hydrological balances and the contributions made to these balances by the various modes of transport;
- (c) the observed net surface fluxes of heat, momentum and moisture;
- (d) the seasonal shifts of circulation and rainfall including important regional changes such as the monsoons.

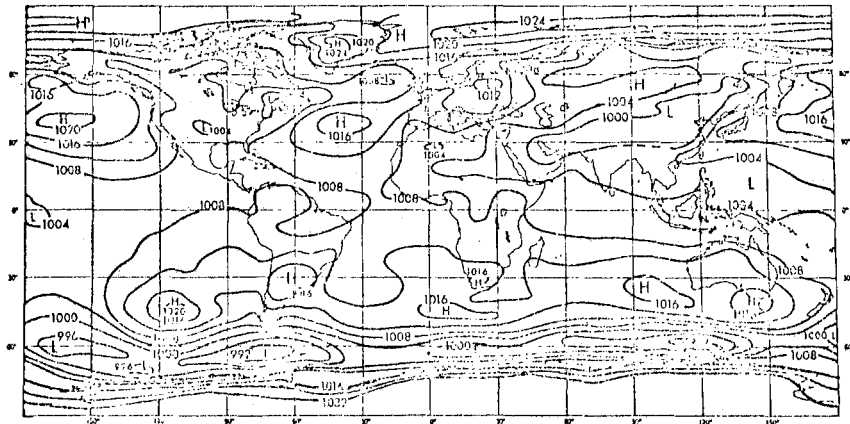
Figures 1(a) and (b), produced by the Met.O. 5-level model, show the computed global distribution of surface pressure for January and July reproducing high-pressure systems over the continents (e.g., the Siberian anticyclone) and low-pressure systems (e.g., the Icelandic and Aleutian lows) over the oceans in winter. The situation is reversed in the summer with the Azores and Pacific anticyclones becoming prominent features. The corresponding wind fields, represented by computed grid-point values in Figures 2(a) and (b), reproduce the middle-latitude westerlies, the trade-winds and doldrums together with the N.E. monsoon over Asia and East Africa in winter and replaced by the S.W. monsoon in summer. The chain of low-pressure centres off Antarctica, greatly intensified during the local winter, and the enhancement of the middle-latitude westerlies in the winter, are also well simulated. The January and July distributions of global rainfall shown in Figures 3(a) and (b), while not accurate in detail, reproduce the major features of the monsoon and tropical rain belts and the desert and semi-arid regions quite well. The fact that the computed values of precipitation and evaporation, averaged over latitudinal zones, agree quite well with observed climatological values as shown in Figures 4 and 5 is particularly encouraging.

The most unrealistic features of this model are the surface pressures in the polar regions that are too high and a monsoon circulation that is too weak.



PRESSURE M.S.L. JANUARY EX.385 MEAN D.61 TO 100

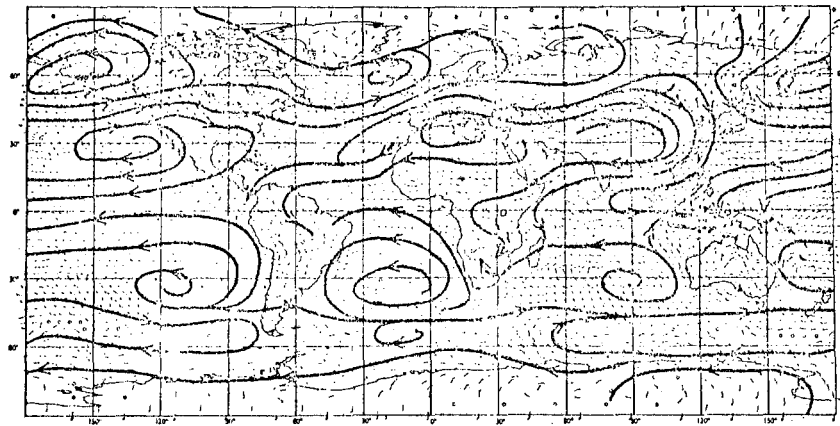
(a)



PRESSURE M.S.L. JULY EX.379 MEAN D.61 TO 100

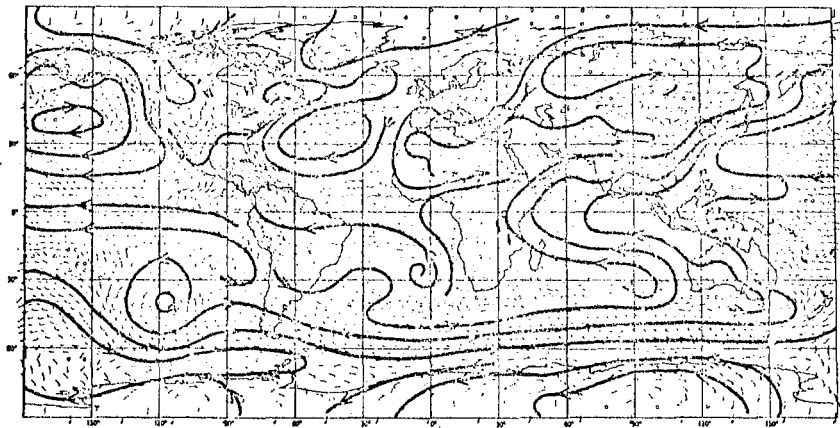
(b)

Figure 1. Simulation of the global distribution of mean sea-level pressure by the Meteorological Office 5-level model for (a) January (b) July.



• 9 SIGMA LEVEL WINDS EX. 385 (JAN) D 61 TO 100 MEAN

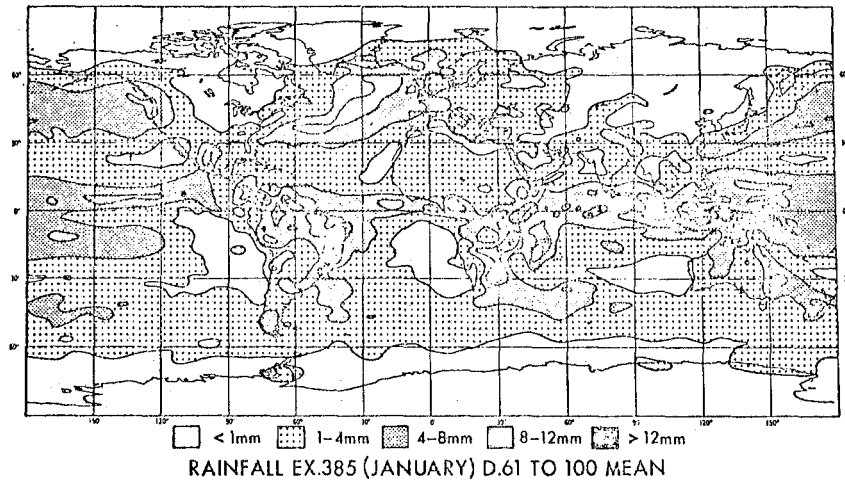
(a)



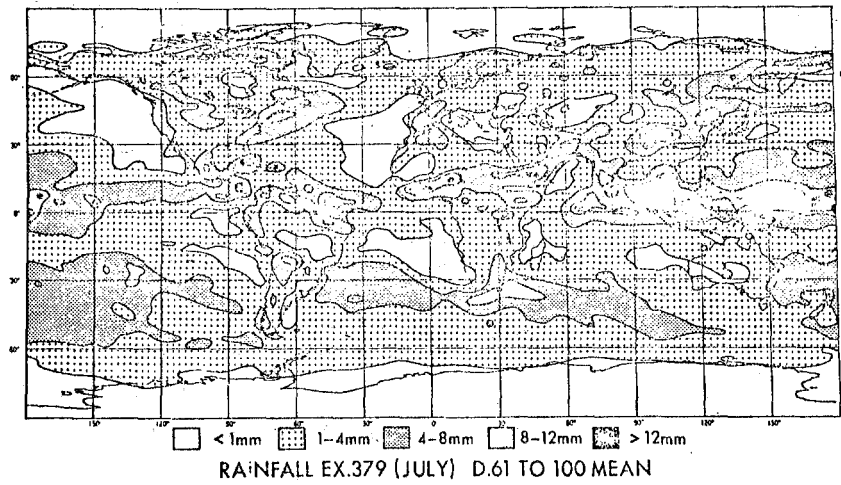
• 9 SIGMA LEVEL WINDS EX. 379 (JULY) D 61 TO 100 MEAN

(b)

Figure 2. Simulation of global winds systems for (a) January, (b) July.



(a)



(b)

Figure 3. Simulation of the global rainfall for (a) January, (b) July.

JANUARY SIMULATION - ZONAL MEAN VALUES

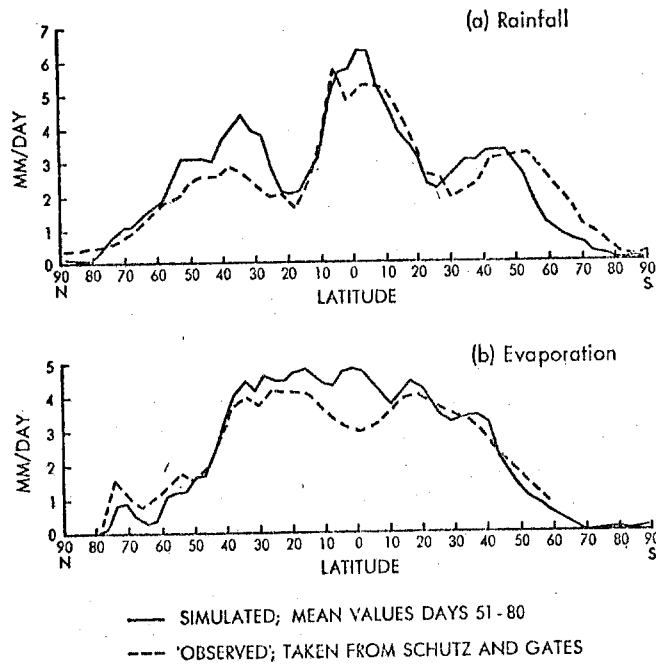


Figure 4. Comparison of zonal mean values of precipitation and evaporation for January as computed from the Meteorological Office 5-level model with climatological values based on observations.

JULY SIMULATION - ZONAL MEAN VALUES

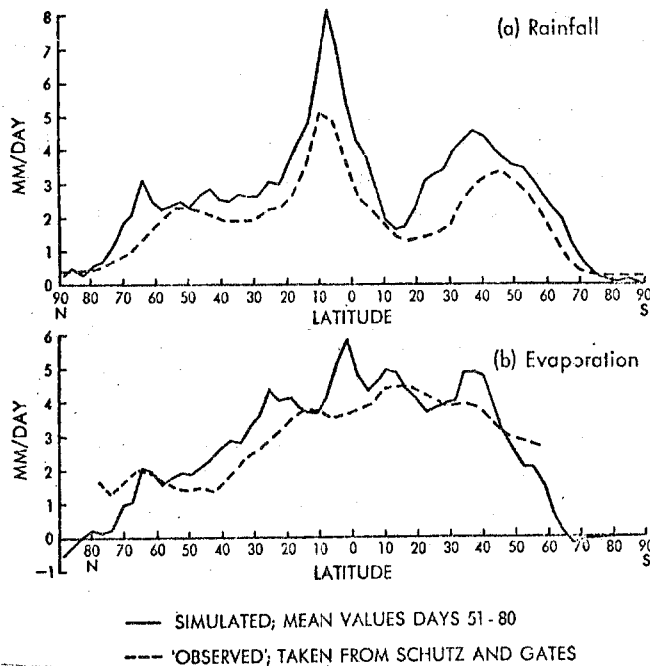


Figure 5. As in Figure 4, but for July.

Some of the defects of the 5-level model have been corrected or improved in the Met.O. 11-level model [5] which has higher resolution, more detailed parameterizations of surface exchanges and boundary-layer fluxes of heat, moisture and momentum, and an interactive ground hydrology in which soil moisture is computed as the difference between rainfall and dew, runoff and evaporation. The power of this model may be demonstrated by its ability to simulate the detailed features of the Asian monsoon which results largely from the differential heating (sensible and latent) experienced by the atmosphere over the oceans and over the land. Figure 6 shows the input of sensible heat minus the radiational cooling into the boundary layer with strongest heating over the desert regions of Arabia, N.W. India and the Indian sub-continent and cooling over the oceans, particularly over the western half of the Arabian Sea.

Figures 7, 8 and 9, taken from Gilchrist [6] show the model simulation for July with the solar declination set at the mid-July value and the sea-surface temperatures held at their average July values. The model monsoon circulation, especially the N-S pressure gradient, is now rather too strong but otherwise the surface pressure field is well simulated with the trough correctly placed over the Bay of Bengal. The general direction of the surface winds, with a direct current on to the southern slopes of the Himalayas, is well represented although the south-west winds off the Arabian coast are too strong. Many important aspects of the rainfall distribution are well simulated, notably the extensive dry area over the western Arabian sea, and the heavy rains over the Himalayas and Western Ghats of India due to the air rising over the mountain slopes. However rainfall over the Ganges valley and northern India is underestimated largely because the model fails to simulate the meso-scale monsoon depressions that originate over the Bay of Bengal.

Having demonstrated their ability to simulate the main features of the present climate, the models may be used with some confidence to investigate the response of climate to conceivable natural changes, for example in the sun's radiation, the land surface and vegetation cover, soil moisture, sea-surface temperatures, etc., and to possible man-made changes to the carbon dioxide, ozone, dust and heat content of the atmosphere and for judging whether these are likely to be distinguishable from natural climatic fluctuations. Also by testing the sensitivity of the statistics generated by the model to perturbations in a particular parameter or combination of parameters, one may hope to discover the underlying causes of climatic change.

However, it may be difficult to assess the significance and reliability of the result particularly if the analysis of the experiment has not clearly revealed the response mechanism of the model and there are insufficient tests to assess the significance of the signal relative to the 'noise' of the model. The response (signal) to a prescribed perturbation will be statistically significant only if the difference in the mean values of the perturbed and standard (control) states can be discriminated from the noise in the model as measured, for example, by its time-averaged response to random perturbations in the initial conditions leaving the boundary conditions fixed.

There is a general impression that the models exhibit less variance than the real atmosphere, if for no other reason than that the boundary conditions such as sea-surface temperature are prescribed. If this is so, it may be easier to detect a

Sensible heating of the Boundary layer of Model B (11 layers)

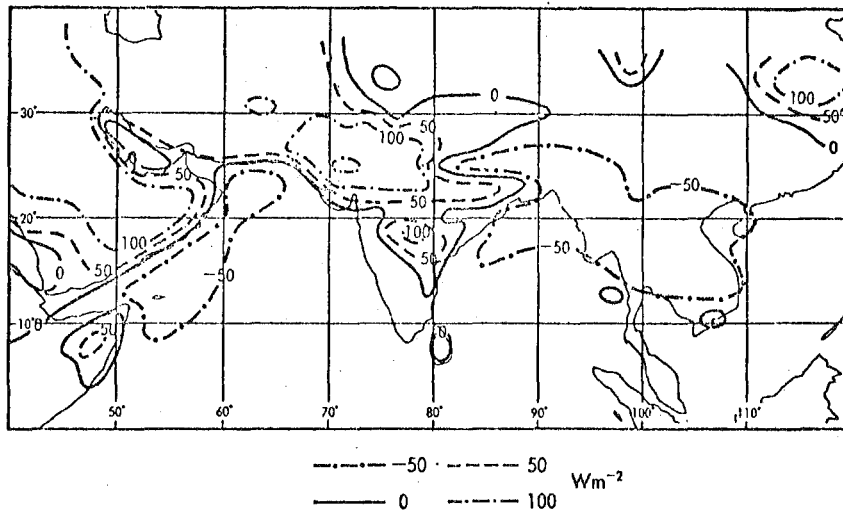


Figure 6. The net input of sensible heat into the lowest layer of the Meteorological Office 11-level model over the region of the Asian summer monsoon in July.

11-layer Model Surface Pressure

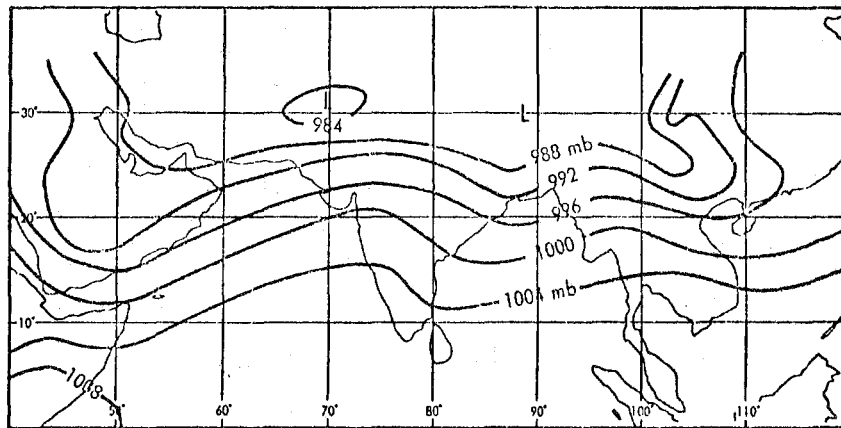


Figure 7. The computed mean sea-level pressure distribution over the monsoon region for July.

11-layer Model Winds at $\sigma = .987$

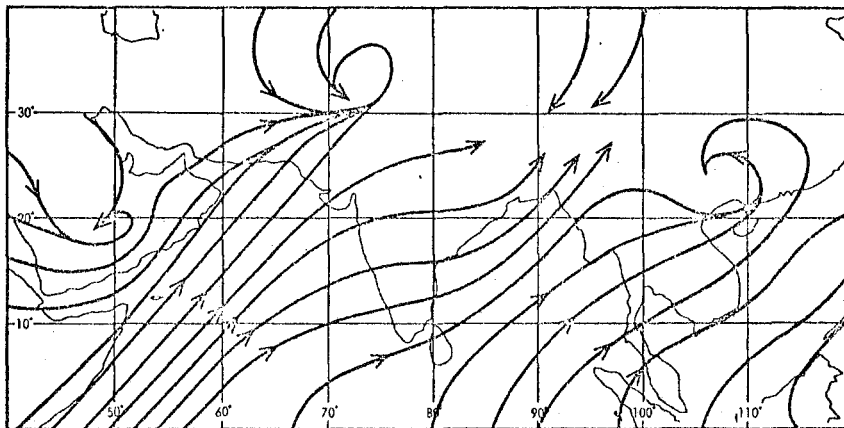


Figure 8. The computed average low-level flow (stream lines) at the lowest ($p/p_s = 0.987$) level of the 11-level model for July.

11-level model Rain

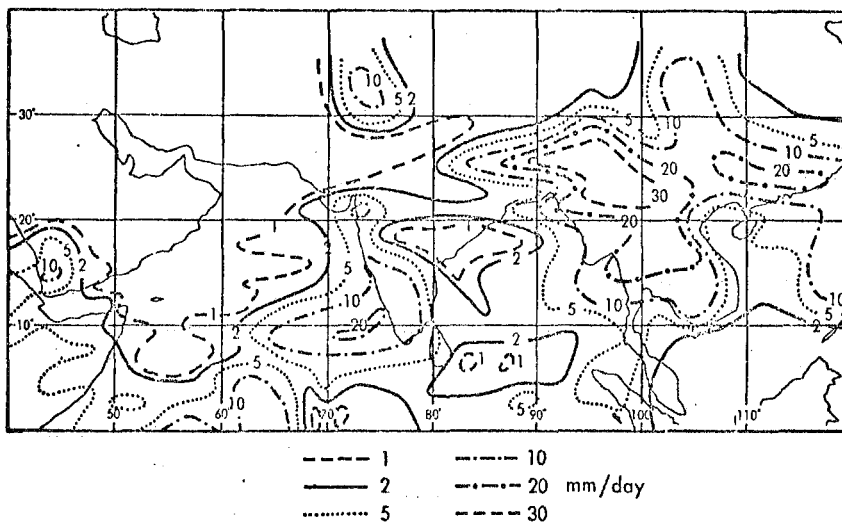


Figure 9. Computed average monsoon rainfall distribution in mm/day for July.

perturbation signal above the noise in a model than in the real atmosphere. It therefore seems important to compare not only mean values but also the models' simulated variance with observations.

4. Some possible natural perturbations of climate

In seeking possible natural causes of major climatic fluctuations one may contemplate changes in the external forces or agencies acting on the atmosphere, internal changes within the atmosphere-ocean system itself or, more likely, an interactive combination of both. It seems likely that the global climate could be modified by changes in:

- (a) the incoming solar radiation;
- (b) the atmospheric composition, e.g., the carbon dioxide, dust, ozone or water vapour content;
- (c) the cloudiness;
- (d) the albedo (reflectivity) of the Earth's surface through changes in soil moisture, vegetation, ice and snow cover;
- (e) the oceanic circulation leading to changes in sea-surface temperature and the transport of heat and moisture.

4.1 Variations in solar insolation

Since the sun is the primary source of energy for driving the global atmospheric circulation, it is natural to consider, as likely to exert some control on the climate, possible variations in either the sun's output or, at any rate, variations in the intensity of the solar radiation reaching the Earth.

A simple radiative heat balance calculation indicates that a 1 per cent change in the solar constant would cause the mean equilibrium temperature of the Earth's surface, with an average albedo of 0.3, to change by 0.6 deg C. A more detailed computation by Wetherald and Manabe 7, based on a simplified dynamical model of the global circulation with fixed cloudiness and in which the ocean is treated as a wet surface for evaporation but has no thermal capacity and transports no heat, indicates that a 2 per cent increase in the solar constant would produce a rise of 3 deg C in the mean global surface temperature, but a decrease of 2 per cent would produce an average temperature drop of 4.3 deg C - see Figure 10. The induced changes are calculated to be much greater near the poles than at the equator because of the marked changes in snow cover and in albedo. The most marked effect was upon the precipitation where a 6 per cent change (from -4 per cent to +2 per cent) in the solar constant produced a 27 per cent increase in the area-mean rates of precipitation. There was a disproportionately greater decrease in the rate of snowfall because the poleward retreat of the zone of sub-freezing surface temperatures shifted the latitude of maximum snowfall away from the highly baroclinic zone of high total precipitation in middle latitudes. Because of the limitations and simplifications of the model the actual numerical magnitudes of the computed changes cannot be

regarded as reliable within a factor of two. This particular model which allows the ocean-surface temperatures to change in accordance with the local radiation balance, with no heat storage or transport in the oceans, and fixed cloudiness, almost certainly exaggerates the changes in the mean surface temperature and precipitation. Even so, the implications are that a 1 per cent change in solar constant would change the surface temperature by only 1-2 deg C and the rainfall by about 5 per cent.

Since the solar output appears to change by a good deal less than 1 per cent, even during solar flares, it is not surprising that weather or climatic events show little correlation with the sunspot cycle.

However, on much longer time scales, the intensity of the solar radiation incident on the top of the atmosphere varies due to secular changes in the Earth's orbit with periodicities of about 96 000, 40 000 and 20 000 years. These fluctuations are much larger than any observed variations in the solar output. Ten thousand years ago, the incoming annual solar radiation was about 1 per cent greater at 65°N latitude than at present and 25 000 years ago it was 2 per cent less than at present.

The seasonal effects are even greater; for example, at 10 000 BP (Before Present) the radiation received in the summer half year was 4 per cent greater at all latitudes than at present whilst at 25 000 BP it was about 2 per cent less. Mason [8] and Hays et al. [9] have demonstrated that these variations in the incoming solar radiation coincided quite well with the major advances and recessions of the ice sheets in the northern hemisphere during the last half million years. Mason also showed that the deficiencies/excesses of radiative heating are sufficient to account for the formation/melting of the ice and the corresponding temperature changes of several deg C in polar and middle latitudes.

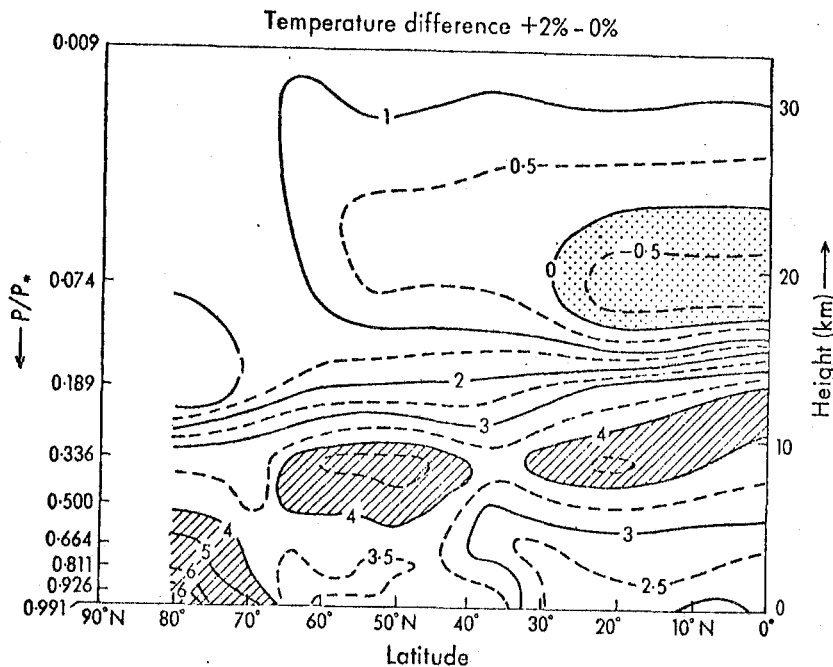


Figure 10. Computed changes in zonal mean temperatures caused by a 2 per cent increase in the solar "constant" (from Wetherald and Manabe, 1975).

Additional support comes from an experiment with the 5-level model in which the effects of variations in the Earth's orbital parameters on global temperatures around the northern summer solstice were assessed by running two integrations, each for 60 days, one representing the solar insolation for the present day and the other for conditions prevailing 10 000 years ago. The model, in this experiment, contained an interactive radiative scheme with three cloud layers and, to avoid its thermal structure being determined by the initial sea-surface temperatures, the ocean was given a depth of 2 metres. Figure 11 shows the computed differences in zonal temperatures, averaged over the last 10 days of June, the atmosphere being warmer everywhere 10 000 BP when the Earth received about 7 per cent more solar radiation in June than at present, with surface temperatures 6 deg C higher in the Arctic basin and 4 deg C higher at 30°N.

This shallow ocean model no doubt allows a greater atmospheric response than would be obtained with a realistic ocean model interacting with the atmospheric model over many years. Indeed in a similar experiment with fixed ocean temperatures, the atmospheric temperature changes are reduced to about one-third of those in the shallow ocean model. One would expect the "true" result to lie between these two extremes.

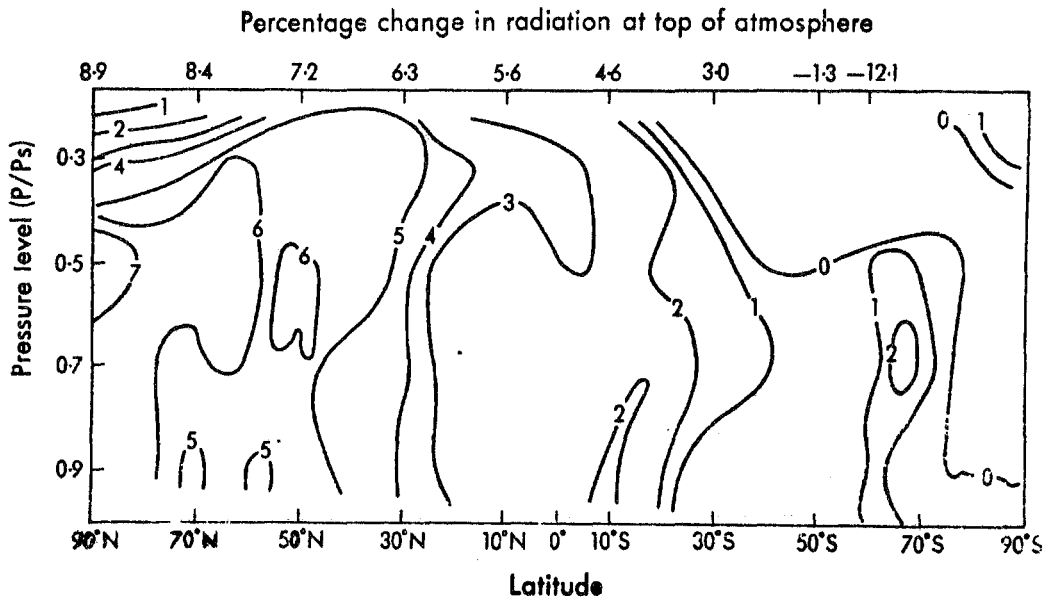


Figure 11. Changes in zonal mean June temperatures caused by changing the Earth's orbital parameters from their present-day values to those obtaining 10 000 years ago.

4.2 Changes in surface albedo and soil moisture

Since, on average, the Earth's land surface reflects back about 15 per cent of the solar radiation, but with variations from about 8 per cent for dark green vegetation to about 80 per cent for freshly fallen snow, widespread changes in vegetation, ice/snow cover or soil moisture could produce a significant change in the heat balance of the earth and hence in climate. On the whole man's activities tend to raise the Earth's reflectivity and so reduce the fraction of solar radiation available to warm the land surface. Simple calculations indicate that a 10 per cent change in the reflectivity of the land surface would change the mean global surface temperature by about 1 deg C.

4.2.1 Melting of the Arctic ice

In an experiment with the Meteorological Office 5-level model, reported by Newson 10, the Arctic sea ice was assumed to melt and be replaced by a water surface held at 0°C. The major effects of removing the ice, apart from the obvious one of warming the polar regions, were to weaken the intense polar anticyclone, to diminish the strength of the middle-latitude westerlies and their associated depressions, and to produce a significant cooling of up to 8 deg C in middle latitudes especially over the United States, eastern Siberia and western Europe as shown in Figure 12. This latter, rather unexpected result, serves to illustrate the limitations of intuitive judgements in dealing with such highly interactive, non-linear systems.



Figure 12. Changes in northern hemisphere surface temperatures produced by replacing the polar ice by water at 273 deg K (from Newson 1973).

4.2.2 Simulation of an ice age

A similar lesson emerges from a numerical experiment in which Manabe and Hahn ^[11] compare the simulations of the atmospheric circulation in the GFDL 11-level model using modern and ice-age boundary conditions. The surface conditions for 18 000 years ago, the peak of the last glacial maximum, have been reconstructed by the CLIMAP Project ^[12] in terms of sea-surface temperatures, land- and sea-ice, surface albedo and topography. Earlier opinion held that the extensive ice cover must have strengthened the meridional temperature gradient, intensified the Hadley circulation and therefore increased the tropical precipitation. However the model experiments indicate quite a different pattern.

The total global rainfall was 10 per cent lower in the ice-age simulation, the reduction over land being 31 per cent but only 1 per cent over the oceans. The global average surface temperature fell by 5.4 deg C, the average drop over land being 7.7 deg C but only 4.4. deg C over the oceans. The increased albedo of the continents during the ice age, due to extensive ice sheets and sparse vegetation, produced lower tropospheric temperatures and higher surface pressures relative to the surrounding oceans. The resulting land-sea pressure gradients strengthened the outflow of continental air accompanied by enhanced sinking and drying out of the air over the continents, reduced precipitation and increased aridity. This tendency was particularly marked over the tropical continents in conformity with recent geological evidence of drier conditions in tropical Africa and South America during the Pleistocene. The model results suggest some compensating increase of precipitation over the tropical and sub-tropical oceans.

4.2.3 Effects of surface albedo and soil moisture and desertification

Stimulated by the interest and concern over the recent droughts in the Sahel region of Africa, Walker and Rowntree ^[13] carried out model experiments to investigate the regional effects of changing the soil moisture of the Sahara using a limited-area and simplified version of the Meteorological Office 11-level model. Comparisons were made between one set of simulations in which the Sahara desert, placed between moist zones representing the North African coast strip and the savanna region to the south, was made initially dry with no soil moisture, and another series in which the Sahara region was made initially wet with 10 cm of soil moisture. In the first series, shallow depressions crossed the region but produced little precipitation because there was no surface moisture to feed and maintain them. In the second case the surface temperatures over the wet ground fell by as much as 20 deg C, cooling extended up to heights of 5 km, and major depressions developed producing widespread rain, heavy in places, which persisted during the 20 days of the experiment. It appears that once an area of this size becomes wet it tends to maintain itself in this state.

In fact rainfall anomalies in this part of Africa do tend to persist once they become established early in the season, and also tend to persist from year to year to give groups of wet and dry years. The reason may well be that both dry and wet regimes tend to be self sustaining through the positive feedback effects of soil moisture assisted by changes in vegetation cover and albedo. Lack of vegetation will

result in higher surface albedo and the consequent radiation deficit in the lower atmosphere would, according to Charney [14], require a sinking motion and mid-tropospheric inflow of air to maintain the heat balance and this, in turn, leads to additional warming and drying and therefore maintenance of desert conditions.

However, calculations made with the GISS 9-level GCM by Charney et al. [15] indicate that when the ground is moist enough to allow significant evaporation the situation is much more complicated. The main effect of an increase in surface albedo is now apparently to reduce evaporation and cloud amount so that the planetary albedo is actually reduced. The consequent increase in direct solar heating of the ground is, however, more than offset by a decrease in the downward long-wave radiation from the reduced cloud cover so that the total absorption of radiation (solar and long-wave) at the ground is reduced, leading in fact to lower evaporation. This result again illustrates the danger of anticipating, by intuitive judgements or over-simplified models, the behaviour of such a complex system with so many feedback mechanisms.

4.3 Influence of anomalies in sea-surface temperature

There is evidence both from model experiments and from direct observations to suggest that large-scale, persistent anomalies in ocean-surface temperatures, produce anomalies in the atmospheric circulation. Forcing of the atmosphere by the ocean is especially noticeable in the tropics but the influence of tropical sea-surface temperature anomalies sometimes spreads into middle latitudes.

During the winter of 1962-63, the coldest in Britain for 250 years, a large area of the eastern tropical Atlantic Ocean was up to 2.5 deg C warmer than normal as shown in Figure 13. Rowntree [16] found that when this anomaly was inserted into the Meteorological Office 5-level model it produced an area of low surface pressure with a deficit of 7 mb centred west of the Bay of Biscay and an extensive area of high pressure with rises of up to 13 mb centred just east of Greenland. The modified circulation resulted in a strong easterly flow over the British Isles reminiscent of that which produced the very cold winter of 1962-63.

5. Some possible man-made perturbations

5.1 Direct heating of the atmosphere

Since the total sensible heat generated by human activities is at present of order 0.01 per cent of the total solar input to the atmosphere and Earth, the global effects are well below a level that can be either calculated or detected. However, within the next 50 years, the input of waste heat due to man's activities is likely to increase greatly, particularly because of the industrialization of many regions that are now under-developed. Washington [17] used the NCAR GCM to investigate whether there might be changes in global climate as a result of man-made input of 300 TW spread according to the present population. He concluded that he could not detect a systematic change above the inherent variability of his model. Llewellyn and Washington [18] carried out a second experiment in which it was assumed that a large part of the eastern United States was heating the atmosphere at the rate now achieved only by Manhattan Island, i.e., at 90 W m⁻². The resulting temperature increases at low levels in the region were as high as 12 deg K but there was little effect elsewhere or at high levels.

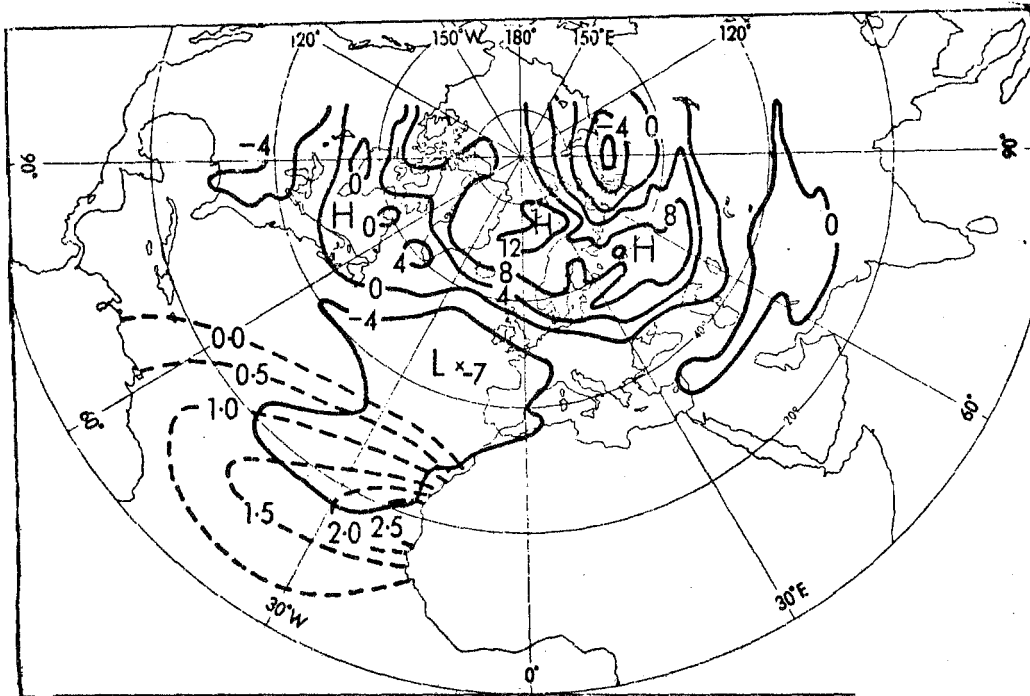


Figure 13. Changes in surface pressure (in mb) produced by introducing the observed anomaly of high sea-surface temperature (broken lines) into the Meteorological Office 5-level model.

The Meteorological Office 5-level model has been used in similar 'megalopolis' experiments in co-operation with scientists at IIASA. They have confirmed that it is difficult to detect systematic effects of the heat inputs.

There is likely to be a continuing large demand for energy beyond the time when fossil fuels provide an economic source and one possible solution will be to construct very large nuclear power plants over the oceans where the waste heat can be most easily dispersed. The possible impact of such energy 'parks' on the global climate has been investigated by scientists at the Meteorological Office and at IIASA using the Meteorological Office model. Inserting 300 TW, the same as in Washington's experiment, but concentrating it in two locations, one off S.W. Ireland, the other off Japan, the model showed a very large global response which, if realistic, would alter the climate significantly over most of the northern hemisphere. With half this heat input, the response was less but still large and widespread. Since 150 TW is about 20 times the present world consumption of energy, it may well be that the climatic effects of waste heat during the next 50 years will be much less than in these experiments.

5.2 Climatic effects of increasing carbon dioxide

The concentration of carbon dioxide in the atmosphere has increased by about 15 per cent during this century and is currently rising at about 1/3 per cent per

annum due largely to the burning of fossil fuels. Since it strongly absorbs the long-wave radiation emitted by the Earth's surface, higher concentrations of carbon dioxide should produce higher temperatures in the troposphere by the so-called greenhouse effect but, because the CO₂ in the stratosphere emits more infrared radiation to space than it absorbs, there should be a corresponding cooling of the stratosphere.

Early estimates of the warming due to increased CO₂ were exaggerated because they were based on simple, globally-averaged, one-dimensional models in which the enhanced downward flux of infrared radiation was assumed to heat the Earth's surface rather than the Earth-atmosphere system as a whole, no allowance being made for the redistribution of the radiative heating by atmospheric motions.

More sophisticated one-dimensional models, [19, 20], making some allowance for the vertical transport of heat by convection and for the radiative properties of water vapour and clouds, provide estimates for the globally-averaged increase of surface temperature T_s , due to a doubling of the CO₂ concentration to 600 ppm, ranging from 1.0 to 3.0 deg K depending upon the vertical distributions of temperature, humidity and cloud cover. Using a model with fixed relative humidity and global average cloudiness, with a penetrative convection scheme that adjusts the vertical temperature profile to near the moist adiabatic lapse rate, Rowntree and Walker [21] obtain $\overline{\Delta T_s} = 1.4$ deg K independent of the surface temperature itself. But, using a simpler convective scheme which adjusts the temperature profile to a fixed lapse rate of 6.5 deg K km⁻¹, they calculate $\overline{\Delta T_s} = 1.9$ deg K for $T_s = 293^\circ$ K rising to $\overline{\Delta T_s} = 2.2$ deg K for $T_s = 300^\circ$ K.

Although most good one-dimensional models indicate that a doubling of CO₂ concentration would produce an average rise of surface temperature of between 1 and 3 deg K, none of them properly represents the atmospheric dynamics nor possible feedback mechanisms involving cloud, snow and ice cover, and so the numerical results must be considered uncertain perhaps by a factor of two or more either way. Moreover such models are unable to provide estimates of geographical variations in the heating effects which can only be obtained from much more complex three-dimensional models. The only such calculation so far published is that by Manabe and Wetherald [22] using a limited-area version of the model described in Section 4.1 above with no seasonal variations. Starting from an isothermal atmosphere at rest, the model equations were integrated over a period of 800 days, the results being averaged over the last 100 days to give equilibrium climates for both the present concentration of carbon dioxide and for double this concentration.

Doubling the carbon dioxide content everywhere raises the temperature of the model troposphere and cools the stratosphere as shown in Figure 14. The increase in the average global surface temperature is 3 deg K, with a maximum of 10 deg K in polar regions caused partly by the retreat of the highly-reflecting ice and snow surfaces and partly by the general thermal stability of the lower troposphere limiting convective heat transfer to the lowest layers. In the tropics this warming is spread throughout the entire troposphere by intense moist convection and so the temperature rise is smaller. Doubling the carbon dioxide also increases the intensity of the model's hydrological cycle, the average annual evaporation and precipitation both being increased by about 7 per cent.

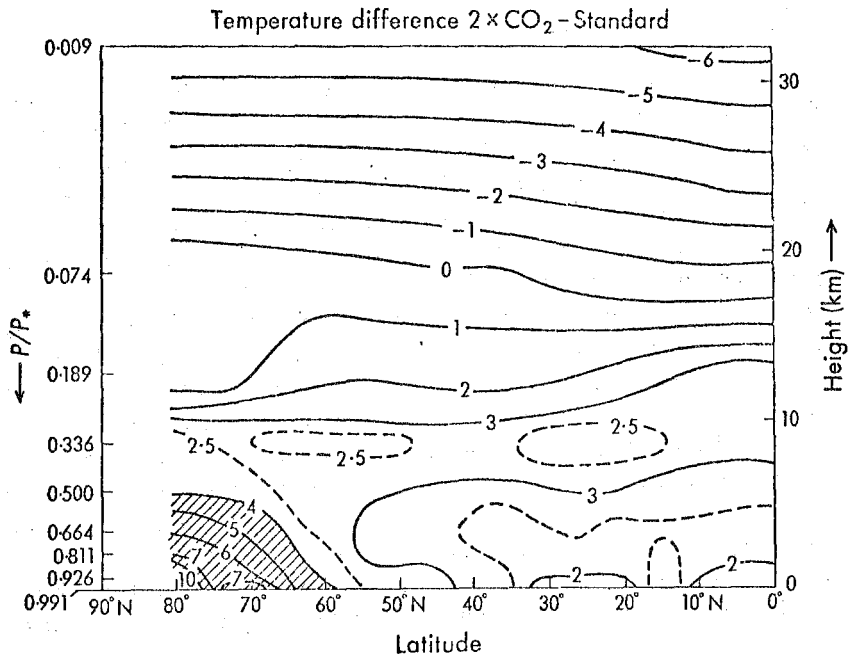


Figure 14. Computed changes in zonal mean temperatures (deg K) caused by doubling the carbon dioxide content of the atmosphere (from Manabe and Wetherald, 1975).

However, since the cloudiness in the model is fixed and the ocean is represented by only a wet surface incapable of storing or transporting heat, the predicted changes are almost certainly exaggerated. Even so, they indicate that the 15 per cent increase in carbon dioxide since 1900 has probably not increased average global surface temperatures by more than a few tenths of a degree and polar temperatures by more than 2 deg K. A doubling of carbon dioxide, on the other hand, could well cause average global surface temperatures to rise by 1 deg K with considerable regional and local variations and rises in polar regions of perhaps 6 deg K, with an uncertainty factor of perhaps two either way. The timing of such changes is a matter of debate with estimates depending heavily on projections for the future rates of fossil fuel consumption and the take-up of carbon dioxide by the oceans and the biosphere. Should the atmospheric carbon dioxide continue to increase at the present rate the concentration will double by about the year 2050 but some projections put it as early as 2030.

Because even the best of present estimates are so uncertain, a detailed investigation of the effects of increasing carbon dioxide using a much more sophisticated model that will represent interactions between the atmosphere, oceans and cryosphere more realistically, and be capable of predicting changes of cloud cover and their effects on the radiation balance, now deserves high priority. Since the energy reflected or emitted to space by clouds amounts to nearly one half of the incoming solar radiation, a change of only 1 per cent in the total cloud cover could mask the effects of a 25 per cent increase in carbon dioxide.

5.3 Effects of stratospheric aerosols

The fact that temperatures in the northern hemisphere actually fell during the period 1940-70, despite a steady increase in the concentration of carbon dioxide, has been attributed to a simultaneous increase in the aerosol (dust) content of the atmosphere. Although the atmospheric turbidity even at remote sites increased markedly after 1963, the transmittance of direct solar radiation being reduced by 2 per cent, this was almost certainly caused by a large volcanic explosion in Bali and now, with measurements almost back to pre-1963 values, there is little evidence that the dust content is increasing significantly. Following the Bali eruption, temperatures in the lower stratosphere rose by several degrees but the rise of average global surface temperature was only 0.3 deg K according to Angell and Korshover ²³. This observation is consistent with the results obtained from an experiment on the Meteorological Office global model extended from 11 to 13 levels to span both the troposphere and stratosphere. The insertion of a stratospheric layer of dust, sufficient to intercept 4 per cent of the incoming solar radiation produced local heating of up to 10 deg K due to absorption of radiation by the dust but there were no discernible effects at ground level. This hardly supports the thesis that cooler climatic epochs in the past may have been caused by volcanic eruptions.

6. Depletion of stratospheric ozone

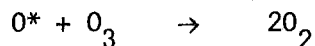
Ozone is formed in the stratosphere through the photochemical decomposition of molecular oxygen into atomic oxygen by ultra-violet radiation:



the atomic oxygen then combining with molecular oxygen in the presence of a third body M to produce ozone:



This basic cycle is completed as O_3 is decomposed by ultraviolet light:



with the net result $2O_3 \rightarrow 3O_2$.

Ozone may also be destroyed by chemical reactions involving nitrogen oxides, hydrogen, chlorine and other minor species, the concentration of ozone at any given height in the stratosphere being determined by the balance of all the chemical processes and by the physical transport of the ozone by the atmospheric motions.

6.1 The role of nitrogen oxides - the Concorde problem

The most important of the chemical reactions, accounting perhaps for more than 50 per cent of the natural destruction of ozone, involve the various oxides of nitrogen designated by the general symbol NO. Especially important is:

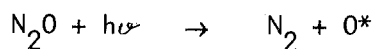


with NO formed by:



the net result being $2O_3 \rightarrow 3O_2$.

Production of nitric oxide, NO, in the stratosphere is governed largely by the rate at which nitrous oxide, N₂O, diffuses up from the troposphere where it is produced by the bacterial decomposition of fixed nitrogen in the soil and upper layers of the ocean. N₂O, which has no known sink in the troposphere, is destroyed in the stratosphere by photolysis:



Other nitrogen oxides are removed by chemical reactions involving hydrogen, e.g.



the nitric acid being washed out in the troposphere by rain.

These are only a few of the more than one hundred chemical reactions that have been suggested as playing a role in the ozone cycle but in many of these neither the concentrations of the species nor the reaction rates are well established.

Johnston ^[24] suggested that the injection of nitrogen oxides into the stratosphere by supersonic aircraft would cause additional destruction of the ozone which, in turn, would cause an increase in the intensity of ultraviolet light reaching the Earth and hence increase the incidence of skin cancer. He suggested that there might also be significant climatic effects. The early calculations were based on inadequate knowledge of the natural concentrations of NO_x in the stratosphere and of the reaction rates of many of the chemical processes, and largely ignored the role of the air motions in distributing the NO_x from the aircraft exhausts through the stratosphere.

However, as a result of a recent intensive research programme (Murgatroyd et al.) ^[25] co-ordinated by the Meteorological Office, and similar programmes in the United States and in France, considerable progress has been made in measuring many of the chemical species from high-level balloons and aircraft, including Concorde itself; in studying the potentially important chemical reactions in the laboratory; and in building complex models of the stratospheric air motions and photochemistry to calculate both the natural concentrations and distribution of ozone and their possible perturbations - see, for example, Tuck ^[26] and Thrush ^[27].

Although many details remained to be settled and new chemical reactions were continually being suggested, there was in 1975 a general consensus of opinion that 500 Concorde's each flying an average of 5 hours per day would reduce the total ozone by no more than 1 per cent and that such a small reduction could not be distinguished from the much larger natural fluctuations. However, since then, Burrows *et al.* [28] have measured the rate constant for the reaction (7) and find it to be about an order of magnitude greater than assumed hitherto. This will result in the more rapid conversion of $\text{NO} \rightarrow \text{NO}_2 \rightarrow$ nitric acid and hence lower rates of depletion of ozone by NO according to reaction (4). Indeed, according to Thrush [27], the overall effect of the emission of nitrogen oxides by Concorde's flying below 18 km might be a small increase rather than a small depletion of ozone. In any case, the small number of supersonic transport aircraft likely to fly during the next decade will have no detectable effect on the ozone or the climate.

6.2 The depletion of ozone by chlorofluorocarbons

In 1974 Rowland and Molina [29] suggested that the chlorofluorocarbons CFCl_3 and CF_2Cl_2 , commonly known as Freons 11 and 12, when released into the atmosphere from aerosol canisters, refrigerators and air-conditioning units, will be carried up into the stratosphere where they will be decomposed by ultraviolet radiation to produce free chlorine atoms that would catalyze the destruction of ozone by the following reactions:



the result being $\text{O} + \text{O}_3 \rightarrow 2\text{O}_2$ with the Cl atom returning to its original form to take part in another cycle. The free chlorine atoms may find a temporary sink in the form of HCl produced either from methane according to

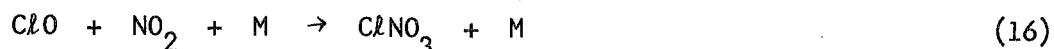


but are eventually restored to the cycle through the action of OH radicals viz:



Methane, hydrochloric acid and the odd hydrogen species OH , HO_2 have all been detected in the stratosphere.

The impact of the $\text{Cl}-\text{ClO}$ reactions may also be further reduced by the formation of chlorine nitrate in the fast reaction



The concentration of free Cl atoms is largely determined by the concentration of HCl and this, in turn, is largely determined by the production of OH radicals according to the reaction



The most recent calculations, using simple one-dimensional models in radiative equilibrium and no dynamics, but involving all the reactions (1) to (16) and including the fast rate constant of (7) reported by Burrows *et al.* [28] suggest that the depletion of total ozone by chlorofluorocarbons is likely to be about twice that of earlier estimates. Thus if the annual global production were to be held at the present rate of 700 000 tonnes (to which the United Kingdom contributes about 6 per cent) their concentration would build up cumulatively over many years and reach a steady state at about 10 times the present level by the year 2100 and reduce the total ozone by about 14 per cent. It would be about 25 years before the ozone was depleted by 5 per cent - about the smallest long-term change that could be detected above the natural fluctuations even if it were not masked by offsetting increases of ozone due to increasing carbon dioxide or other effects.

6.3 Effects of increased carbon dioxide on stratospheric ozone

Carbon dioxide is not directly involved in ozone chemistry but influences it through its effect on stratospheric temperatures. It is shown in Section 5.2 above that because the carbon dioxide in the upper stratosphere emits more infrared radiation to space than it absorbs, an increase in its concentration cools the upper stratosphere where most of the ozone is formed. The ozone-producing reaction $\text{O} + \text{O}_2 + \text{M} \rightarrow \text{O}_3 + \text{M}$ proceeds rather faster at lower temperatures whilst the ozone dissociation reactions proceed more slowly. The cooling of the stratosphere is, however, partly compensated by absorption of ultraviolet and visible radiation by the increased ozone.

Groves *et al.* [30] have recently computed these effects by following the progress of 28 simultaneous reactions thought to be of the greatest importance in ozone chemistry (they include, for example, all the reactions listed in the last two sections), all assumed to take place in a vertical column at 34°N containing realistic vertical distributions of water vapour and carbon dioxide and a single layer of cloud reflecting 30 per cent of the incident solar radiation. Diurnal and seasonal variations of solar insolation are included and rates of vertical turbulent mixing were taken from the Meteorological Office 13-level global three-dimensional model but otherwise dynamical effects are ignored. The vertical temperature profile is determined by calculating heat transfer between levels by both radiative exchange involving all the absorbing gases and by convection. This temperature profile is updated in the chemical kinetics scheme every 30 min and the resulting ozone profiles are used to update the radiative heat transfer calculations.

In a reference experiment the CO₂ volume mixing ratio was set at 290×10^{-6} (290 ppm by volume), the value estimated for 1925, and the model was run for 10 years by which time it achieved a stationary state. In subsequent experiments the CO₂ concentration was varied from 250 to 600 ppm and the results expressed as deviations from the reference experiment. Figure 15 shows the computed temperatures and ozone concentrations for the reference experiment over a two-year cycle with the seasonal variations. These computed values are in reasonable agreement with observation except that they indicate an ozone maximum in the lower stratosphere in summer whereas, in fact, the maximum occurs in the spring.

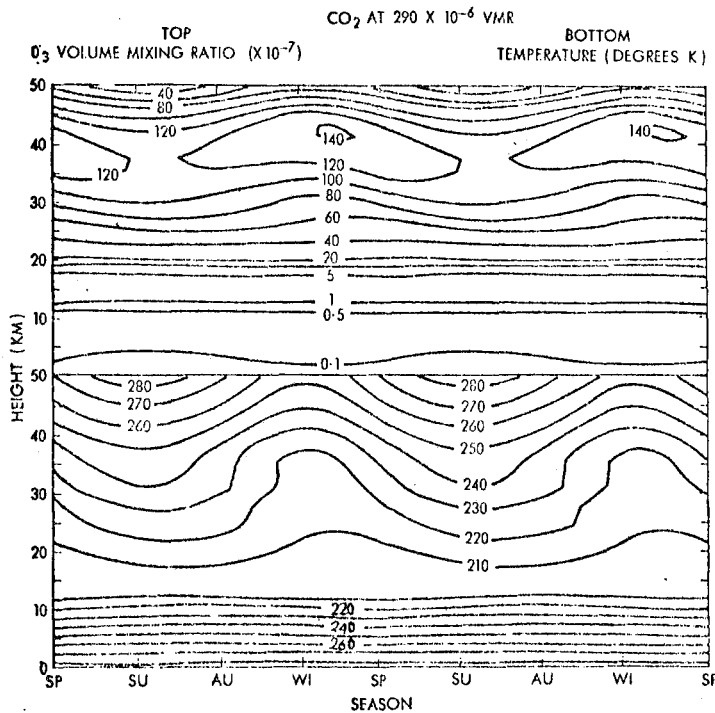


Figure 15. Computed temperatures and ozone concentrations in a vertical column at 34°N and their seasonal variations with the carbon dioxide concentrations at its present value of 290 ppm (from Groves *et al.*, 1978).

Figure 16 shows the computed changes of temperature and ozone concentration caused by increasing the CO₂ concentration from 290 to 600 ppm. At heights of 40 km the temperatures are lower by about 10 deg K in summer and by about 7 deg K in winter, the corresponding increases in ozone being 14 and 11 per cent. At 30 km the temperature changes are respectively -6 deg K and -4 deg K, in good agreement with the results of the Manabe-Wetherald global model shown in Figure 14, but the ozone increases by only 4 per cent in the summer because the large increase at higher levels absorbs much of the incoming ultraviolet radiation and allows less to penetrate to the 30 km level.

The predicted percentage changes in the total integrated ozone content of the vertical column for various CO₂ concentrations, together with the years in which they may, on extrapolation of present trends, be expected to occur, are as follows:

Concentration of CO ₂ (ppm)	Percentage change in total ozone	Year
250	-0.9	-
275	0.0	1800
290	0.8	1925
325	1.3	1972
425	2.3	2020
600	5.5	2050

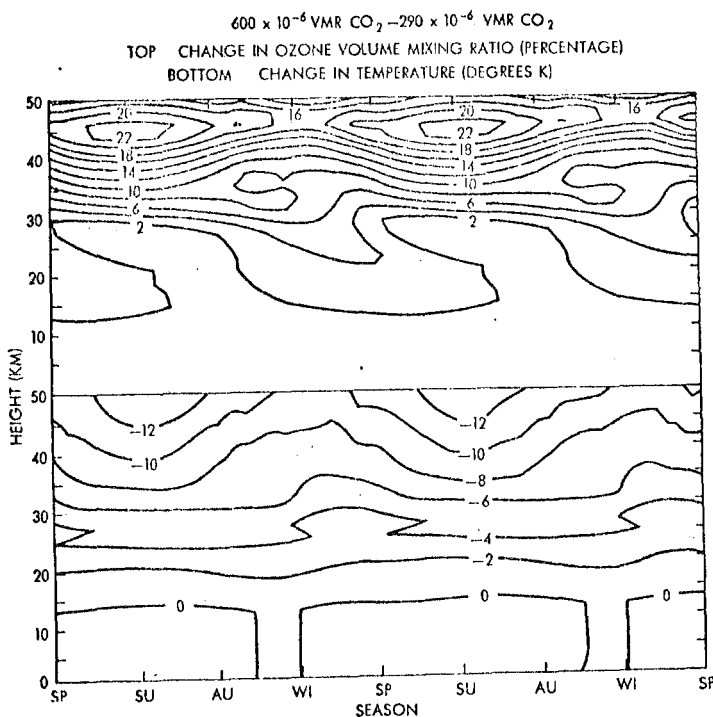


Figure 16. Computed changes in the temperature and ozone concentration of the column when the carbon dioxide concentration is increased to 600 ppm (from Groves et al., 1978).

The longest and most reliable series of total ozone measurements, made at Oxford and Arosa, indicate that annual mean values have increased steadily at 0.1 per cent per annum or 5 per cent overall since 1925. This increase is an order of magnitude greater than that predicted by the model calculations but the observations also have their uncertainties and do not firmly establish the magnitude as distinct from the sign of the long-term trend.

It is interesting, nevertheless, to compare the model predictions of a 2.3 per cent increase in ozone by the year 2020 and 5.5 per cent by 2050 with the predicted decreases of about 8 and 10 per cent attributed to the continued release of chlorofluorocarbons. Since there are uncertainty factors of perhaps two in all these estimates, it seems possible that any depletion of ozone by chlorofluorocarbons may be at least partly compensated by increases caused by increasing carbon dioxide.

6.4 Effect of ozone depletion on climate

The Meteorological Office 13-level three-dimensional global model has been used to investigate the likely climatic effects of reducing the concentration of stratospheric ozone by up to 50 per cent. Figure 17, taken from Murgatroyd et al. 25, shows that this produced a marked cooling of the stratosphere, by as much as 20 deg K at 40 km altitude over the tropics, but there were barely detectable changes in temperature or rainfall in the lower atmosphere. These calculations suggest that neither supersonic aircraft nor the continued release of chlorofluorocarbons is likely to have a discernible effect on the climate during this century.

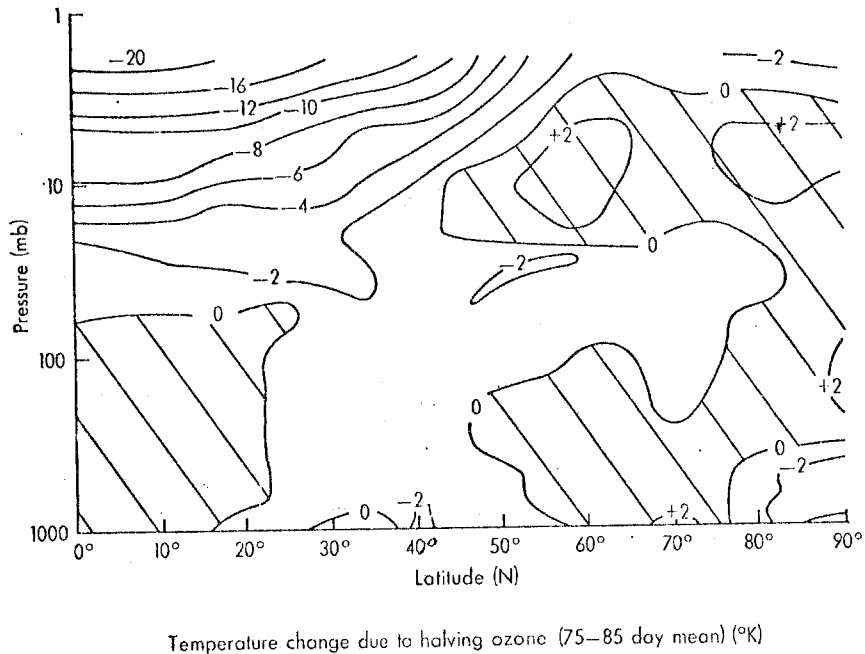


Figure 17. Computed changes in the air temperature (deg K) as a consequence of halving the concentration of the stratospheric ozone in the Meteorological Office 13-level three-dimensional model (from Murgatroyd *et al.*, 1975).

7. Prediction of climatic variations

The prediction of future climatic changes, as distinct from the simulation and sensitivity studies just described, poses a formidable scientific problem. It is especially difficult because it is not possible, as in daily weather forecasting, to verify such long-term predictions against observation. They imply the use of a predictive model whose inherent skill can be judged only by its ability to simulate present and past climates and marked changes such as seasonal variations.

Prediction of climatic variations induced by changes in external forcing factors such as the incoming solar radiation, changes at the boundaries of the climatic system, or by man's activities presupposes that these stimuli can be predicted accurately in advance. Aside from this, the precision of any climatic prediction, expressed as a set of climatological statistics, will be limited by random or spontaneous internal fluctuations within the real climatic system and its accuracy limited by the extent to which these fluctuations are reproduced in the model.

It is argued, I think pessimistically, that a further fundamental limitation arises because advanced dynamical models, even when heavily constrained by fixed or only slowly changing boundary conditions, produce rather different sets of climatological statistics when started from slightly different initial states, and that such differences may mask any climatic fluctuations being sought. However, this apparent inter-determinancy of model behaviour probably arises because these complex models, which tend to outstrip available computing resources, are usually run for only relatively short periods; when integrated over long periods they are likely to approach

an equilibrium state and produce climate statistics largely independent of the transient features of the initial state.

There is, however, the possibility that the real climatic system, being highly non-linear, may be able to exist in two or more quasi-stable modes and change rather abruptly from one such state to another. The transitions between glacial and interglacial epochs are suggestive of such changes. If such transitions are externally induced, as suggested in Section 4.1 above, then they are probably predictable, at least in principle. If, however, they can arise spontaneously from internal reconfiguration of the climatic system, they may not be predictable by models that are damped sufficiently to ensure dynamical and computational stability.

At present we are restricted to using incomplete and imperfect models to study their response and sensitivity to specific external stimuli and to prescribed changes in their internal structure. Provided that these perturbations are large enough to produce responses that are detectable within the noise generated by the model, their effects can be estimated within certain confidence limits. However, determination of the magnitude and statistical significance of any such response requires a series of model experiments together with their proper controls and a great deal of computation.

However, attempts are being made to circumvent the vast amount of computation required by explicit dynamical models, by developing statistical-dynamical models in which the properties and structure of individual large eddies (e.g., cyclones) would not be computed explicitly but their transport properties would be parameterized in terms of the large-scale features of the wind and temperature fields. However, there are considerable difficulties in this approach and many results of detailed global circulation models would be required to carry out the parameterization. Moreover, because the cyclones, which are so important in converting potential energy into kinetic energy, tend to be suppressed in simple models with poor resolution, it is difficult to envisage a realistic climate model that does not handle them properly. But it may be that low resolution models with clever parameterization of the unresolved scales, will determine the mean fields and the important eddy transports with sufficient accuracy to indicate how the climate will respond to identifiable long-term variations in external forcing and boundary conditions even if they are unable to predict smaller and more subtle fluctuations that, nevertheless, may have serious economic and social consequences.

ADDITIONAL NOTE

Recent calculations on the effects of doubling the concentration of CO₂

The UK Meteorological Office has commenced a series of model experiments to obtain firmer estimates of the climatic effects of increasing the concentration of atmospheric carbon dioxide including regional and seasonal changes. Using its 11-level global model, integrations have been carried out through the annual cycle using a fully interactive radiation scheme and periodically up-dated cloud-cover and

sea-surface temperatures with present and doubled CO₂ concentrations and with present or enhanced sea-surface temperatures. With present sea-surface temperatures (climatological values updated every five days) a doubling of CO₂ leads to a rise in average global land-surface temperature of only 0.4 deg K and a corresponding 1 per cent increase in precipitation but with strong latitudinal and regional differences. Maximum heating occurs in the Arctic basin with temperature rises of up to 4 deg K in winter. With sea-surface temperatures maintained at 2 deg K above their present values, doubling of CO₂ leads to a rise of 2.7 deg K in average global land-surface temperature and a corresponding 3 per cent increase in rainfall but again with strong regional variations and maximum warming in the Arctic. The first experiment probably minimises the effects of increased CO₂ whilst the latter experiment, like that of Manabe and Wetherald, probably overestimates them. The 'true' answers probably lie somewhere in between but confident estimates will require combined atmosphere/ocean models with a comprehensive treatment of the interaction between them.

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A SCENARIO OF POSSIBLE FUTURE CLIMATES -

NATURAL AND MAN-MADE

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1. Introduction

The scenario to a historical film is based partly on the factual background and partly on a subjective and artistic interpretation that includes personal judgements and values. However, a scenario of possible future climates should not contain any subjective interpretation of the available evidence on past climates although critical assessments and comparative evaluations of the data are acceptable and indeed are indispensable. Episodes of past climates may serve as empirical models but, since climate never exactly repeats itself, it is necessary to examine to what extent the boundary conditions (composition of the atmosphere, distribution of land and sea, heights of mountains, etc.) may have changed since the periods on which the models are based.

Instrumental observations have been made on an increasing scale since about 1650, and are providing valuable data on climatic variation and variability. However it should be borne in mind that this period of some 300 years is extremely small compared with the age of the Earth which is estimated at about 5 thousand million years. As regards the practical task of constructing past climates, fairly reliable knowledge is restricted to the past 550 million years and is derived from various forms of fossil life which have provided approximate (or proxy) data giving fairly reliable estimates of climatic parameters.

In the overview papers of Bolin, Hare, Gates, and Munn and Machta, it has been shown that variability is a natural property of climate. Natural effects may tend towards a more extreme and cooler climate like that which prevailed during the 17th - 19th centuries. In addition to natural fluctuations of climate the increasing role of man-made effects seems likely to lead towards a warmer climate.

On a global scale, warming or cooling are apparently most marked in the polar regions where the changes, whether warming or cooling, are larger by a factor of 3 or more than those occurring in low and middle latitudes. Global cooling can be produced by a sequence (cluster) of heavy volcanic eruptions or by a decrease of

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solar radiation for which there is limited but controversial evidence. One may also mention the hypothesis of large-scale surges of west Antarctic ice (see Section 2.3 below).

Global warming may result from an increase of solar radiation or from projected increases in the quantities of gases like CO₂ and N₂O in the atmosphere (see overview paper by Munn and Machta). Other man-made effects are either smaller (tropospheric particles, direct input of heat to the atmosphere) or act more slowly (cooling through increase of surface albedo following deforestation, overgrazing and other desertification processes).

In the following sections some historical episodes of warmer or cooler climate are described, mainly with respect to changes in large-scale rainfall patterns. Such rainfall variations can be produced by shifts of the large-scale wind belts which are mainly dependent on the temperature difference between equator and pole. Moreover a weakening of the tropical branch of the circulation suppresses the upwelling of cold, deep ocean water along the equator and off some coastal regions. This in turn substantially increases oceanic evaporation from warm water and thus also precipitation.

Section 2 deals with past warm episodes such as may be expected in the future with growing CO₂ content of the atmosphere and with an increasing greenhouse effect. Here one should add the role of other infrared-absorbing trace gases, which can be approximately expressed in terms of a "virtual" CO₂ content. This results from an addition of say, 50 per cent (100 per cent) to the CO₂ increase above the present level (330 ppm), taking into account an estimated increase of nitrous oxide (N₂O), methane (CH₄), ammonia (NH₃), halocarbons and other gases. The relationship between a representative temperature increase (excluding the polar regions) and the virtual CO₂ content is given by a model of Augustsson and Ramanathan [2], with two versions representing two extreme assumptions. The equivalent level of "real" CO₂ is given by subtracting the above-mentioned increase produced by other trace gases. Table 1 gives the selected paleoclimatic warm episodes, together with the level of warming, and the virtual and real CO₂ content; the latter figures may be taken as representing the best available estimates. It should be stressed that these increased CO₂ levels are purely hypothetical: in general we have no evidence that such levels occurred in these past epochs.

Section 3 deals with cold episodes. Here the "Little Ice Age" (1550-1850) may serve as a rather well-known model. The possibility of a transition towards a real new ice-age will also be discussed. In Section 4 some conclusions are given.

The examples given in Sections 2 and 3 are factual and, as they occurred under somewhat different boundary conditions, they cannot be expected to repeat themselves exactly. However, they may serve as empirical models of what could happen with a man-made global warming or with a natural global cooling.

Table 1

Combined Greenhouse Effect, CO₂ Content and Paleoclimatic Phases

ΔT	Paleoclimatic Phase	Virtual CO ₂ (ppm)		Real CO ₂ Content (approx.)			
		CTT	CTA	CTT		CTA	
				+100%	+50%	+100%	+50%
+ 0.5 K	Perception of Warming	365	395	342	350	360	375
+ 1.0	Medieval warm phase (900-1050 AD)	420	490	370	386	405	432
+ 1.5	Holocene warm phase (~ 6 000 BP)	475	580	398	422	450	492
+ 2.0	Eem Interglacial (~ 120 000 BP)	530	670	426	460	495	555
+ 2.5		590	760	455	500	540	610
+ 4.0		Ice-free Arctic Ocean (12-2.5 x 10 ⁶ years BP)	780	1150	555	630	740

ΔT = expected temperature increase; BP= Before Present Time

CTA, CTT = versions of Augustsson-Ramanathan Model; CTA assumes constant cloud top level
CTT constant cloud top temperature

1) i.e. with a 50% (100%) contribution of trace gases to the increase of virtual CO₂

2. Warm episodes in climatic history

2.1 Mediæval warming

According to the evidence collected by Lamb [3], the early Middle Ages were the warmest period of the last millennium. The peak differs slightly in timing from area to area - but the most remarkable period was between about 900 and 1050 AD. It was characterized by unusually warm and hospitable conditions in Arctic latitudes, with a disappearance of sea-ice in the East Greenland Current, cereal cultivation in Iceland and Norway up to 65° N, and settlements as far north as Ellesmere Island and the New Siberian Islands. During this period forests advanced in Canada up to 100 km north of their present limit, simultaneously with an upward shift of many vegetation zones in European mountains, indicating a temperature increase of about 1 deg C (Table 2). Frequent droughts occurred all over Europe south of 60° N, including the Caspian Sea which stood at -32 m, i.e. lower than now, even though much water is today removed for irrigation. The Dead Sea was nearly as low as now. Some parts of the Sahara were apparently wetter [4] and reports indicate crossings by horse caravan, and cattle rearing around Kufra Oasis, now near the centre of aridity. China and Japan had warm summers, but in China severe winters have also been reported.

In North America, evidence of extended agriculture from this period has been found in Illinois and Iowa, including a remarkable urban centre there [5]. Tree-ring data from the Californian mountains also indicate higher temperatures but lower rainfall. The same was true in S.W. Colorado. Evidence from the Tropics is very scanty. Cambodia and the Yucatan flourished during a somewhat drier period. Rains in Ethiopia were concentrated in the southern part (with Nile floods low, Lake Turkana high). No data are available from India. Even from the Antarctic coast reports of long-lasting warming exist, together with a marked drought and forest-fire period in New Zealand.

The interpretation of these data [3] suggest a northward shift of the cyclone track by 3-5 latitude degrees to 60-65°N, and high pressure conditions over Europe similar to the warmest and driest summers of the period 1931-60. During winter, a similar pattern occurred in the north, not infrequently related to a "blocking" pattern, with severe winters and extended droughts, especially in Eastern Europe. This pattern is obviously consistent with the marked retreat of Arctic sea-ice. Since the speed of the East Greenland Current is greater than the melting rate of ice floes, their disappearance indicates a retreat of the Atlantic drift-ice to latitudes north of 80°N. Cooling in northern Greenland after 1160 led to a marked advance of glaciers in the Alps and other mountains and later to a southward resurgence of Arctic sea-ice, around 1320, together with extreme climatic anomalies and severe famines in Europe. A 200-year drought period in Iowa and Illinois finally led to mass emigration. This cold wave was a forewarning, after several interruptions, of a transition towards the Little Ice Age in the period 1550-1850 AD (see Section 3).

2.2 The Holocene warm episode

The retreat of the melting ice-domes of North America and North Europe after the last ice-age maximum 18 000 years before present (BP) has been described in some detail by Lamb [3]. Additional evidence has recently become available and

shows that, while the less voluminous Scandinavian ice-sheet finally disappeared about 8 000 BP, the North American ice-sheet still covered about half of its original area, disintegrating after a catastrophic incursion of the sea into the Hudson Bay (see Figures 5 and 6 of overview paper by Hare). Separate ice sheets remained, the Labrador ice disappearing after about 4 500 BP, and some plateau ice fields in interior Baffin Island have apparently survived until today. These events created a marked asymmetry of the atmospheric circulation between 8 000 BP and 6 500 BP, lasting to a lesser degree until 4 500 BP. During this period Eurasia and Africa experienced the warmest epoch of the last 75 000 years, but eastern North America remained relatively cool, certainly during summer, with frequent outbreaks of polar air. The result was a predominance of southwesterly winds over the Atlantic and an intensification (and northward shift) of the Gulf Stream and its branches. During winter, this situation led to the development of frequent outbreaks of polar air over central and eastern Europe, extending with abundant precipitation into the Mediterranean and northern Africa.

This episode was indeed a benign climatic epoch for many peoples. The present description refers mainly to its peak, about the year 6 000 BP. All the following data are given in radiocarbon years; their conversion into calendar years, with possible differences of up to 12 per cent, is still a matter of some uncertainty. Insufficient time-resolution of available data does not yet allow consideration of fluctuations on a 100-year scale.

Forest boundaries in western Canada and in western Siberia were situated 200-300 kms further north than at present; the summer temperature has been estimated 2-3 deg C higher. Sub-Arctic forest also covered the northernmost islands in Norway and the whole of the Taimyr peninsular. This warm period, however, came to an end around 4 800 BP, when a polar outbreak lasting not more than about 200 years displaced the forest boundary in Canada more than 300 kms towards the south. Nearly simultaneously with that abrupt event, many important climatic shifts towards a "neoglacial" climate similar to the Little Ice Age from 1550 to 1850 AD have been observed in other areas, together with a step by step desiccation of the present Arid Zone (see below). The inner Arctic experienced (with some delay) its warmest Holocene period only after 4 500 BP, with seasonally open waters in the fjords and along the northern coasts of Spitzbergen, Greenland and Ellesmere Island, allowing Siberian driftwood to reach these coasts up to 83°N. However, there is no indication that the core of the present Arctic drift-ice between Greenland, Alaska and eastern Siberia disappeared.

In the sub-Antarctic ocean, the much more rapid shrinking of the (mainly seasonal) Antarctic drift-ice led to a warming peak as early as 9 000 BP. Similarly, this warm period had already started before 7 000 BP in eastern Siberia, where no major ice sheets had been formed during the last glaciation. At Lake Biwa in central Japan, the warm period was initiated before 8 000 BP. As early as 10 500 BP (the start of the Holocene), a major and rather abrupt shift between glacial and near-present conditions occurred all over the globe and the tropical oceans became slightly warmer than now. Increasing evaporation raised the water vapour content of the tropical air, leading to a rapid expansion of the tropical rain-belt and rain-forests (which had been drastically reduced during the last ice age). The occurrence of

thermophilous species in the European and Asiatic forests 6 indicates somewhat higher temperatures and rainfall. Some estimates of the basic climatic parameters given by Lamb 3 for the period around 6 000 BP and for certain other climatic stages of interest are reproduced in Table 2.

Table 2

Climate Estimates, England and Wales

	Temperature (°C)			Rainfall ¹⁾		Evaporation ¹⁾	Runoff ¹⁾
	Year	Jul/Aug	Dec/Feb	Year	Jul/Aug	Year	Year
Atlantic 6 000 BP	10.7	17.8	5.2	110-115	?	108-114	112-116
Little Optimum, 1150-1300 AD	10.2	16.3	4.2	103	85	104	102
Little Ice Age, 1550-1700 AD	8.8	15.3	3.2	93	103	94	92
Recent warm period, 1916-50	9.4	15.8	4.2	932mm		497mm	435mm

1) per cent of 1916-50 average

Source: 3

The waters of the Kuroshio, between Taiwan and Japan, were up to 6 deg C warmer than now. At mid-latitude coasts the probable temperature increase was 1.5-2 deg C. In other continental areas the increase was lower, at least in north-eastern North America. In the area between 85° and 95°W, a triangle with prairie vegetation ("The Prairie Peninsula") expanded into Wisconsin and Illinois, with a maximum extent near 7 000 BP. Together with some areas in south-west Siberia and eastern Turkey, this is one of the few areas which was drier than now 7. Permafrost retreated in eastern Siberia several hundred kilometres northward of its present position: a similar retreat in Canada and Alaska probably occurred because of the northward extension of forest and tree lines. In the mountains the upper tree line shifted upwards by 100-150 m, thus indicating a warming of about 1 deg C.

In subtropical latitudes, the present-day arid areas experienced wetter conditions than today. Since the temperature was everywhere higher or similar to present values, this humid climatic phase must have been related to higher precipitation - as caused by higher evaporation of the tropical oceans. This was correlated with a weakening of the subtropical anticyclones and of the trade winds, obviously leading to a marked reduction of area and intensity of coastal and equatorial upwelling of cool, deep ocean waters.

Perhaps the most surprising feature of the Holocene warm period is the now well-authenticated occurrence of a marked humid period in the Sahara and in the deserts of Near and Middle East 4,5,8,9. In this period the concept of a parallel shift of climatic zones towards north or south as suggested by seasonal variations, cannot be taken any more as a general explanation. Recent evidence supports the idea that in some periods the winter-rains at the northern flank and the tropical summer-rains at the southern flank increased or decreased together, thereby creating a tendency towards a synchronous shrinking or expansion of the arid belt. During the second maximum period of the moist Holocene period, between 6 500 and 5 000 BP, the remnants of the North American ice and frequent cold outbreaks within the European-African sector caused an expansion of the Mediterranean rains towards the south. Extended high-tropospheric troughs across the Sahara triggered tropical low-level disturbances, which crossed the arid zone, as "Saharan depressions" and initiated more frequent rains even in the central belt between Lat. 21° and 26° N, especially in the transitional seasons.

In addition to many other Saharan lakes that are now dry, Lake Mega-Chad (at least 40 m higher than now, with an area near 320 000 km², comparable to the present Caspian Sea; at its peaks overflowing to the Benue-Niger catchment) demonstrated the quite different hydrological situation that then existed. Even in the currently hyper-arid centre of the Sahara between Kufra Oasis and Tibesti Mts. - with less than 5 mm of rain per year today - permanent or periodic rivers were flowing, indicating at least 250 mm and perhaps up to 400 mm of rainfall per year. The grasslands were utilized by many groups of cattle-raising nomads 10.

Similar evidence has been found throughout the arid belt of the Old World between Mauritania (about 17° W) and Rajasthan (about 77° E), including the Afar-Danakil depression and interior Arabia. At the margin of Thar desert (India and Pakistan) with an average recent rainfall near 250 mm, these rains increased to values between 500 and 800 mm during a long moist period, lasting from 10 500 BP until about 3 600 BP 5. Here once more monsoonal summer rains and extratropical winter rains were both increased.

In this whole area of Africa and Asia, gradual desiccation began about 5 500 BP in several steps interrupted by relatively wetter periods. It is noteworthy that the early high civilizations (the Old Empire of Egypt from 1st to 4th dynasty, the Near East urban centres, the Indus Culture) started during or at the end of this humid period, and thus had to combat increasing desiccation. North of about Lat. 35° N, however, the displacement of the winter rains towards the south led to a dry period in Anatolia and Iran; the best evidence for this has been found from a lowering by 300-400 m and salinization of Lake Van in eastern Anatolia.

During this same period, climatic conditions in Australia were quite similar to Africa, with increased precipitation at the northern and southern margins of the desert together with a slight warming even at altitudes above 2 500 m in the mountains of New Guinea 11. In contrast to this, the available evidence in southern Africa 12 indicates drier, semi-desert conditions on the interior plateau. Evidence for the Holocene climatic history of the arid southwest of the U.S.A. is limited to

the existence of a fresh water lake in central New Mexico during this moist period. In Nevada and California, a marked dry period between 9 500 and 5 000 BP followed a moist period, with high lake-levels between about 13 000 and 10 000 BP.

Detailed diagrams of eustatic sea-level fluctuations, i.e., those caused mainly by variations of the total mass of water in the oceans, have been presented by several authors. Their results show considerable variations from one to another but most authors now assume only minor world-wide fluctuations (less than 2m) at this time. A discussion of this important problem will be given later (Section 2.3 and 2.4).

At this point the question must again be raised: how far can climatic history repeat itself under varying boundary conditions? Two boundary conditions during this warm period were essentially different from today's:

- (i) The presence of limited and thin, but not negligible, permanent ice-sheets only in eastern Canada must have been effective during the Holocene warm-moist period. Their disappearance appears to correspond roughly with the desiccation after 5 500 BP. This is understandable if one takes into account the effect on the circulation pattern in the European sector of a permanent cold source in eastern Canada. This should have favoured, as in modern conditions during spring, a high frequency of blocking anticyclones in the region of the British Isles and Scandinavia. This should occur especially during the warmer seasons, frequently accompanied by deep troughs over east-central Europe, which should extend diagonally into northern Africa, thereby increasing cyclonic activity in the Mediterranean. In the future such conditions could only be expected if, with increasing Arctic sea-ice, a permanent snow cover should develop in the Baffin-Labrador area. During the next century this is quite unlikely (see Section 3.2).
- (ii) The increasing man-triggered desertification processes 13 probably contribute to the slow, gradual desiccation process in late Holocene times (see also overview paper by Hare). In many arid regions (e.g. Rajasthan and Tunisia) representative rainfall data available since 1890 or 1905 do not reveal the existence of an actual downward trend. Several numerical models designed by Charney and other authors 14 analyse the role of man-made destruction of vegetation, which causes increasing surface albedo, and may lead to an intensification of atmospheric subsidence, which in turn inhibits effective rainfall. It is difficult to believe that during a man-made warming a forced change in the circulation pattern could be followed immediately by increasing rainfall over this vast area. Only after the slow reconstruction of a sufficiently dense vegetation cover to decrease the albedo, could the positive feedback effect of desertification → increasing albedo → increasing subsidence → less rainfall → extended desertification be interrupted or reversed. This also presupposes a major, concerted effort to halt and possibly reverse desertification processes, such as soil erosion, deflation, salinization, under increasing population stress.

From argument (i) we should conclude that along the northern margins of the Old World arid belt, no substantial increase of rainfall should be expected from a future warming. At the southern flank some increase might be possible if, as expected, the intensity of the subtropical anticyclones weakens, together with their displacement toward higher latitudes. This would weaken the trade winds of the northern hemisphere as well as coastal and equatorial upwelling, with higher low latitude evaporation and water vapour content. As a more suitable scenario for the future, the warm but drier period 4 000-3 500 BP might be more appropriate; but for this period much less detailed information is available.

From argument (ii) we should conclude that restoring the natural vegetation cover would, under present population pressure, be a difficult problem that might cause a delay of several decades before a reliable long-term increase of rainfall could be achieved in the sub-tropical dry region. Much further research of a truly interdisciplinary nature is certainly needed.

2.3 The last interglacial epoch

Recent investigation - from ocean cores in all latitudes, from continental loess deposits in Austria and Czechoslovakia, and from a fossil bog in northern Greece - have indicated that during the last 2 to 2.5 million years a sequence of at least 17 large-scale glaciations of northern continents has occurred, interrupted by the same number of interglacials with a climate similar to the current period 15. Detailed data are only available from more recent events, especially from the last glaciation from about 73 000 BP until 14 000 BP, which included two major glacial peaks at its beginning and end, and at least five shorter periods with a slightly warmer climate (interstadials). The last interglacial lasted, with two important interruptions, from about 130 000 BP until 75 000 BP. Its climate has been carefully described, for Europe and Asia, by Frenzel 6. Information from North America is hardly adequate, and that from other continents is almost lacking. A more detailed investigation of the climate of the earliest peak of the last interglacial, often referred to as the Eem interglacial, around 125 000 BP is now under way by the CLIMAP group 16 who are evaluating a large number of ocean cores to obtain a realistic estimate of sea surface temperatures and salinities. Since this sub-period is apparently the warmest of all interglacials, a short climatic interpretation will be given here.

In northern and eastern Europe the climate was much more oceanic than at present, mainly due to the high sea-level of about 5-7 m above present values, which isolated Scandinavia from the continent by a marine channel connecting the Baltic with the White Sea. The sea also penetrated deeply into western Siberia, along the Ob and Yenisey flood plains up to 62°N. Table 3 gives a selection of climatic data from Eurasia and North America, with temperatures generally 2-3 deg C higher than today but in some areas even higher, and slightly more humid. In the cool-temperate zone, forests were more warmth-adapted: deciduous trees like oak, linden, elm, hazel and hornbeam prevailed. The occurrence of hippopotamus, forest elephants and lions in southern England is a remarkable feature of this warm climate. The occurrence of temperate forests in eastern Siberia indicates a marked retreat of permafrost up to 57°N; boreal forests extended up to the arctic coastline of that period. The high

temperature estimates suggest a seasonal retreat of Arctic drift-ice far from the coasts, which were, however, inundated by the high sea-levels. Though the marginal parts of the Arctic drift-ice were probably displaced poleward, the central core of the ocean, between Greenland, Alaska and Eastern Siberia, has remained ice-covered at least since 700 000 BP. Worldwide comparison of ocean cores indicates that during this stage the sea-level stood at least 6 m higher than at present, as evidenced in Barbados, Hawaii, New Guinea, Majorca and the lower Thames valley of England.

Table 3

Climatic Differences: Eem-Actual

Area	Temperatures (°C)			Rainfall Annual (mm)
	January	July	Annual	
Denmark	+2	+1-2	+1.5	0
N + C Germany	+1-2	+3	+2.5	0
Central Poland	+3-4	+3	+3	+50
NE Poland	+3-5	+3-5	+5	+50
Byelo-Russia	+5-6	+5	(+6)	0
Central Russia	+9-10	+2	+5	+100
NW Ukraina	+2-3	±0	+1	+50
W Siberia	+4	+3	+3	+100?
Central Siberia	?	?	+6	?
Toronto	+3-4	+2	+2-4	+250
SE Alaska	?	+4-5	?	?
Banks Isl. (72°N)	?	+4-5	?	?

Source: 6

The duration of this earliest peak of the interglacial was only of the order of 10 000 years; it was terminated by an abrupt cooling of relatively short duration, during which global ice volume increased and decreased rapidly, causing a sea-level change of 60-70 m, compared with 100 m during the last glacial episode.

Two other warm phases followed, but with less warmth-adapted forests, and lower sea-levels. A simplified diagram - forest versus tundra - from a peat bog core in SE France (Woillard), indicates the apparent shortness of the two cold

episodes on the continent (see Figure 4 of overview paper by Hare). The second cooling coincides probably with a marked event found in the famous Camp Century ice core from N. Greenland (76°N) known as Greenland Blitz. Similar events at many other places, such as a deep cave in southern France, peat bogs in northern Greece and California, and an ocean core from the Caribbean are also probably correlated.

In several well authenticated mid-latitude interglacials, such abrupt coolings have been observed, with a sub-Arctic or Arctic climate lasting only some centuries or 1-2 thousand years ("abortive glaciations"). Only the Holocene did not experience a similar sudden drop of temperature. The physical mechanism of such abrupt coolings of natural origin - occurring with a recurrence time of the order of some 10 000 years - is unknown. Speculations about the possible role of clustering volcanic eruptions or of Antarctic surges (see Sections 2.4, 3.2) give only hints as to causes.

Little evidence is known from low latitudes: the occurrence of a long humid phase, with a deep lake in the Afar Triangle (west of Djibouti), and also along the West African coast, suggest humid conditions like those of the early Holocene.

2.4 Glaciated Antarctic versus ice-free Arctic

The most fascinating, and also the most controversial problem of the future evolution of our climate is the possibility of a complete disappearance of the drifting ice of the Arctic Ocean. The thickness of multi-year ice - which covers about 70 per cent of the area of the Arctic ice and the bulk of its central core - varies between about 0.5 m (one-year ice) and 6 m, varying with the age of the individual flows. Often quoted figures of an average thickness near 3 m have little statistical significance in this quite inhomogeneous mosaic. The varying area of leads (polynyas) - about 3 per cent during winter up to 15-20 per cent during the melting season (mid-June to August) - plays a significant role in the energy budget of the air-snow-ice-ocean sub-system.

The sensitivity of this system is demonstrated by the large amount of seasonal melting (from above) and freezing (from below), with an average near 50 cm per year; no figure for the interannual variability is available. The system is especially sensitive to the heat flow from the underlying ocean, to the albedo of the ice-snow surface during the melting season, and to the length of the melting season (ending with the occurrence of the first snow cover). Budyko originally discussed the possibility of an artificial removal of the Arctic ice [17]. Later on he designed simplified models [18,19] to indicate that small increases of solar radiation, or an increase of the atmospheric CO₂ content might lead rather rapidly to an ice-free Arctic Ocean. There would be a substantial increase of surface temperature by about 6-8 deg C in summer, but by more than 20 deg C in winter.

Arguments for and against such a drastic evolution have been frequent. Because no existing model realistically includes the physical and dynamical interactions, and the feedback processes between atmosphere, drifting ice and ocean, this problem cannot be solved satisfactorily now. It seems possible that during late winter a thin seasonal ice cover might develop. This would only slightly modify the dramatic change.

It is therefore of particular interest that in climatic history such a pattern existed for a very long time: a strongly asymmetric pattern with a heavily glaciated Antarctic continent existing simultaneously with an ice-free Arctic Ocean, together with a few isolated mountain glaciers in **Alaska** and Iceland. This strong asymmetry started first at the beginning of the Oligocene about 38 million years ago, when substantial Antarctic sea-ice was formed, resulting in widespread glaciation on parts of the Antarctic continent [20], and in a temperature drop of the ocean bottom water of about 5 deg C. The cold and dense bottom water spread (as now) outwards into all oceans, and caused a major world-wide crisis among the deep-sea fauna.

After some further long-term climatic fluctuations, a complete Antarctic ice cap was built during the middle Miocene (14-11 million years ago) as a semi-permanent feature, which was probably still warm, i.e., ice temperatures were near the melting point. This event occurred simultaneously with a sharp increase of volcanic activity whose ash is represented in many ocean cores. The highest peak of Antarctic glaciation - now apparently as a cold and slow-moving ice-dome - was reached near the end of the Miocene (6-5 million years ago), when the global ice-volume was 50 per cent greater than now. At this time the height of the ice-dome must have been several hundred metres higher. This event was accompanied by sharp global cooling, by a 300 km northward spread of Antarctic cold surface waters, and by a high carbonate sedimentation rate in the equatorial Pacific, indicating strong upwelling of nutrient-rich cool water [21]. Seven to ten cyclic temperature changes were observed, with minima as cold as during the cold phases of the glaciation. One of the most important consequences was a eustatic drop of the sea-level of at least 40 m. During this event the Straits of Gibraltar went dry, and isolated the Mediterranean, which evaporated completely 8-10 times to a depth of 3 700 m, and then filled again, leaving a 300-500 m, thick laminated salt layer [22]. This evidence indicates, during a period of about one million years, a cyclic behaviour with a time-scale near 10^5 years, which is uninteresting from the point of view of human affairs.

Long before the present spate of discussions on paleoclimate, Lotze [23] constructed maps of the position of the evaporite belt during past climates, i.e., of the arid zone of playas and sebkhas, where soluble salts sedimented in dry pans. Figure 1 shows the northern limits of the northern arid belt, indicating a southward shift from an average latitude near 47°N in the early and middle Tertiary to 42°N in the Miocene-Pliocene and to 38°N in the Quaternary. Here only the latter comparison is important; the multiple desiccation of the Mediterranean during the final phase of the Miocene only aggravated the arid conditions during the ten million years of this extremely asymmetric type of climate.

During that time even south-central Europe was partly arid, with steppe or desert vegetation near Vienna, [24,25]. Though before these events tropical marine microfossils occurred in the Atlantic up to 58°N , this boundary retreated during the desiccations of the Mediterranean on the eastern side of the Atlantic at least to about 33°N . After the reopening of the Mediterranean, no such tropical species could enter it, while in the Gulf Stream region they still reached north 50°N . As is the case today, such great longitudinal contrast is largely caused by the wind-driven surface currents of the oceans.

Northern Boundary of NHem Evaporite Zone



—	Quaternary	(0-2 Ma)
- - -	Late Tertiary	(5-15 Ma)
.....	Early Tertiary	(30-50Ma)

Figure 1. Displacement of northern boundary of the northern hemisphere arid zone (based on distribution of evaporites such as gypsum, salt, etc.). Source: 23.

Regional temperature and precipitation estimates are quoted in the literature 24,26. Since during this time most of our mountains existed only in rudimentary form, these numerical data cannot be taken as representative of present conditions. This is obvious, for example, in the now arid continental basin of Nevada, or in the Mojave Desert: both areas enjoyed during the late Miocene a rather moist maritime climate near sea-level. Small meridional temperature gradients were probably accompanied, in the northern hemisphere, by large seasonal variations: in the Tropics the area of savanna climates with seasonal rains was much greater than now, whereas the equatorial rain-forest with all-year rain was reduced. This seems to be related to the occurrence of winter snow in the northernmost continents, with quite large seasonal fluctuations of the climatic belts.

In a recent review paper, Maley ^[27] pointed out that during the Miocene the vegetation pattern of the African continent revealed the same marked asymmetry: the southern Sahara was covered with a tropical humid or at least semi-humid vegetation (which persisted in southern Nigeria), while southern Africa and the Zaire basin were dry and sometimes desert. This evidence is still incomplete, but seems to indicate a hemispheric asymmetry of the general circulation substantially greater than now ^[28], though the shape and position of the continents were only slightly different from today. Large-scale glaciation of the northern continents did not start before 2.5 - 3 million years ago. An Arctic drift-ice cover only formed after that date, when the melting waters had covered the Arctic Ocean with a shallow, stable low-saline upper layer ^[29], about 2.3 million years ago.

Thus at least between about 12 and 2.5 million years ago, the simultaneous existence of a continental ice-dome over the Antarctic and a substantially ice-free Arctic Ocean produced marked circulation asymmetries of both atmosphere and ocean. Along the coast of Alaska, well-developed boreal and mixed forests extended more than 800 kms northward of the present limit of some of its trees; the fossil insect fauna in 66°N resembled that which now lives in the Vancouver-Seattle area in 48-50°N. At the same time, the sub-antarctic ocean had a climate as cold as now. This asymmetry was accompanied by an annual temperature difference between Arctic and Antarctic of order 20 deg C, averaged over the troposphere (300-700 mb or 3-9 km), in contrast to the present value of 11 deg C, together with a development of ice and snow in one hemisphere only and thus a strongly asymmetric surface albedo pattern.

The relation between the meridional tropospheric temperature difference between Equator and Pole in individual months, and the simultaneous position of the subtropical high-pressure belt (Figure 2) correctly describes, with present-day data, the seasonal displacements as well as the hemispheric asymmetry of the planetary circulation ^[30]. A simple extrapolation based on a substantial warming of the Arctic atmosphere alone, with nearly constant temperatures at both Equator and South Pole, yields an annual shift of the northern subtropical high-pressure belt from a present value of 37°N to 43-45°N, while the location of the southern subtropical belt remains unchanged at 31°S, in good agreement with the geological record. During summer, the change would probably be small, but during winter the subtropical belt probably may have shifted more than 600 kms to the north, thus drastically reducing the extent of the subtropical belt of winter rains.

This asymmetric displacement of the northern subtropical belt, together with the constancy of the southern subtropical belt, necessarily causes a shift of the position of the "meteorological equator" from 6°N (present average) to about 9-10°N. In this case the equatorial rain belt would probably only occasionally penetrate, during the northern winter, across the equator into the southern hemisphere; its seasonal displacement may have been restricted to the belt between equator and 20°N.

It should be stressed that in the Atlantic and the Pacific the position of the equatorial oceanic upwelling zone, with its strong carbonate sedimentation, is controlled by the disappearance of Coriolis force at the geographical equator. Here any meridional climatic shift can be excluded.

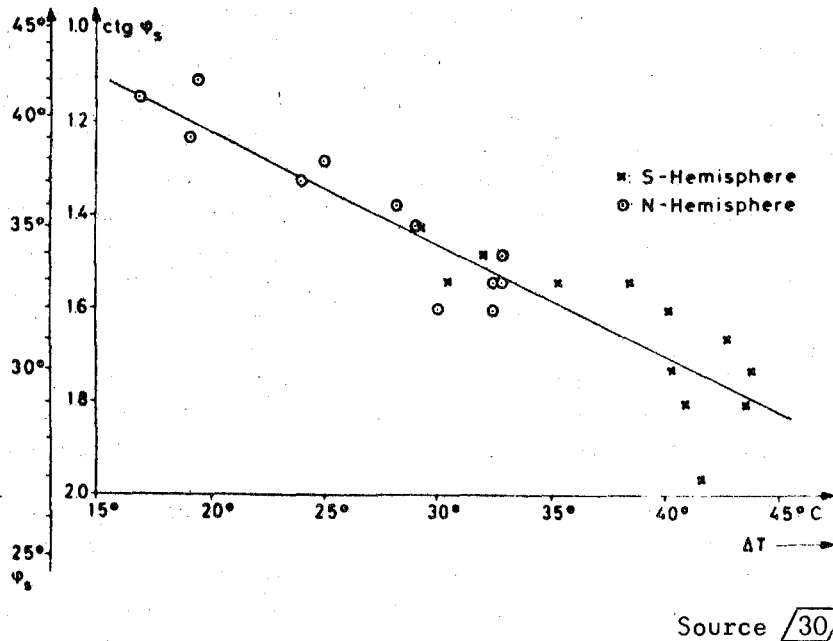


Figure 2. Latitude of the sub-tropical anticyclone belt in all months, plotted against the actual temperature difference (ΔT) between equator and poles, 300 to 700 millibars.

After a possible disappearance of the central core of the Arctic pack-ice in a foreseeable future, the first consequence would be an increase of cold-season snowfall along the northern coasts of the continents and arctic islands, while during summer the low-level stratus above the ice might disappear. Of more importance would be the reduction and northward displacement of the winter-rain belts in the Mediterranean, Near East and southwestern North America, together with frequent summer droughts in the belt 45-50°N and an extension of the subtropical dry areas towards north. Since in the monsoon area of Southern Asia the disturbed circulation patterns are largely controlled by the strong recent uplift of the Tibetan highlands and the Himalayas, no base for a foreshadowing of the effects in those areas of disappearing Arctic sea-ice exists. The same is true for western North America.

In the latitude belt between about 10°S and the equator a semi-arid or even arid climate can be expected, aggravated by increasing frequency of equatorial upwelling and a strong decrease of oceanic evaporation. In the present Sudan-Sahel belt, between about 8°N and 18-20°N, a gradual increase of precipitation might be possible; one of the essential prerequisites, however, should be the conservation of the vegetation (cf. Section 2.2).

The possibility of a world-wide rise of sea-level as caused by a melting of polar ice, should be considered quantitatively. Thinning or even disappearance of

drifting sea-ice would not change the sea-level at all; sea ice remains in floating equilibrium with water. In the individual human time-scale (of < 100 years) any world-wide sea-level rise could be caused only by large-scale surges of continental ice-caps of the order of 10^5 km^3 or more, which would lead (with a density near 0.9) to a sea-level rise of 25 cm per 10^5 km^3 . Only one area is prone to such a surge: that is the "western" part of Antarctica (between South America and 150°W), where the ice rests on a rock basement largely below sea-level [31]. Surges of that order have been suggested for historical times [32] as well as for the post-glacial period [33]; the low probability of such an event should increase with global warming. A gradual transition seems to exist between such surges (with an unknown time-scale) and extended calving of existing ice-shelves. Of even more interest are possible surges of the order of $1\text{-}2 \cdot 10^6 \text{ km}^3$, equivalent to a sea-level rise of 2.5-5 m: the last event of this kind apparently occurred during the last interglacial [34], while the details are still uncertain [52]. The risk of such large-scale surges seems to be small, but certainly not negligible; more detailed investigations should be undertaken.

The possibility of a significant melting of the continental ice-caps is also small. The surface of the Antarctic ice-cap, with temperatures between -20 deg C and -70 deg C and an albedo (reflectivity) of 80-90 per cent can be considered as stable; even a marked warming by transport of warm air would be insufficient for significant melting or evaporation. After the dispersal of the Arctic sea-ice, Greenland ($60\text{-}83^\circ\text{N}$) would probably be affected by much more winter snowfall and also by some warm-season melting, at least at its southern part. The ratio of both processes is difficult to estimate without model computations; but in the worst, and quite unlikely, case an estimated annual net loss of 50 cm water equivalent, would cause a sea-level rise of 2.5 mm per year, to be compared with the present value of 1.2 mm per year. Any possible melting of the Greenland ice glaciers would be a slow process, lasting several millennia, with a total sea-level rise of 6-7 m.

3. Cold episodes in climatic history

In addition to the climatic warming due to the work of man, there exist natural but undetectable effects which may add to any global warming such as:

- (i) a hypothetical increase of solar "constant"; and
- (ii) the absence of large volcanic eruptions during a period of several decades (probably one of the main causes of the 1920-45 warming).

In these cases, developments as described in the last chapter would be accelerated, following a similar pattern. It should be mentioned that the orbital variations of the solar radiation available at the top of the atmosphere during the northern hemisphere summer, passed the last maximum about 11 000 years ago, and were responsible for the Holocene warm period (Section 2.2). The next radiation minimum in Arctic summer and Antarctic winter is expected 7 000 - 13 000 years in the future [35], and is thus merely of academic interest. Its deviation from the present value will be weaker (-11 to -14 Wm^{-2} compared with -20 Wm^{-2} about 25 000 years ago).

A more interesting case is the possibility of a global cooling on the time-scale of some decades or centuries. This case will be considered now in some detail. The following natural effects could cause such a cooling:

- (i) a decrease of the solar constant by about 1 per cent (or more)
- (ii) a cluster of volcanic eruptions, as for example, during the years 1807-1835

We should add, at least for its possible role for the southern hemisphere:

- (iii) an increased frequency of calving from Antarctic ice shelves, as, for example, between 1888 and 1907 (see Section 2.4).

The possibility of a significant variation of the solar radiation, in the visible and near-infrared part of the spectrum, is still hypothetical. The available evidence - gained from direct balloon measurements up to 28 kms [36] or from albedo measurements of Uranus and Neptune [37] - is not yet sufficiently convincing. The meteorological community is still waiting for direct satellite observations with a sufficient degree of accuracy; this should be an important task for the World Climate Programme. Wetherald and Manabe [38] have simulated - as a sensitivity test of their "ocean swamp" model - the changes of climate to be expected after a change of the solar constant of a few per cent (see overview paper by Mason).

A detailed discussion of the climatic consequences of a great number of tabular icebergs in the sub-Antarctic Ocean is difficult, since only a few long records south of 45°S exist. Nevertheless, it has been shown [39], that with an inter-annual increase of the sub-Antarctic ice the zonal circulation of the southern hemisphere increases; simultaneously, warming prevails in the northern hemisphere, together with more frequent zonal circulation patterns. This suggests a northward displacement of all climatic belts across the equator, together with a negative correlation of Arctic and Antarctic temperatures. In contrast to this, a decrease of the sub-Antarctic ice is correlated, with wide-spread cooling and a greater frequency of meridional circulation patterns in the northern hemisphere. In the tropics the sub-Antarctic ice-maximum between 1888 and 1907 [32] was accompanied by a marked climatic shift around 1899, when a relatively wet period - especially on the eastern sides of the continents - was followed by a drier one, lasting until about 1960. At present it is hard to ascertain which polar region plays a greater role in the vicissitudes of tropical rainfall, especially when looking at its marked longitudinal differencies. Here world-wide teleconnexion studies based on an atlas of rainfall-temperature anomalies for each month are badly needed.

3.1 Volcanic events and the Little Ice Age

A most important aspect is the role of volcanic events for global cooling of the lower atmosphere. Recent empirical investigations [40, 41] have verified the old idea of a cooling due to stratospheric aerosol after heavy volcanic eruptions. These eruptions inject large masses of particles and gases into the stratosphere; here the latter are photochemically transformed into a greater number of rather homogenous small particles with a radius of about 0.5 μ m. These minute particles (practically floating in the air) intensify the world-wide aerosol layer at 20-22 kms altitude, produce bright twilight phenomena, absorb solar radiation and heat the surrounding stratosphere by 5-8 deg C. In the troposphere, however, the loss of short wave radiation leads to a weak cooling of the order of 1 deg C on the average near the surface, which can be masked in some regions by warming by warm winds.

Such a global cooling can only be detected by using representative averages for latitudinal zones. At individual stations the natural variability is frequently larger than the cooling trend (see overview paper by Hare). Nevertheless the frequency of cool, wet summers after major volcanic eruptions is remarkable; in Japan, Europe and North America severe crop failures and famines have been reported in the years following some of the largest eruptions (for example, 1766, 1783, 1815, 1835, 1883 42).

The world-wide cool period between about 1550 and 1850 AD - the so-called Little Ice Age - has been established by many investigations which, however, still leave some areas nearly blank, such as tropical South America, the Indo-Pakistan subcontinent, Indonesia, Australia and the tropical Pacific. In the Atlantic - Europe sector, some precursors in the decades around 1190, 1310-30 (with extremely severe famines), and 1430-60 foreshadowed this episode. The Little Ice Age was a period of world-wide glacier advance with frequent cold and wet summers and severe winters, often lasting far into spring, interrupted by some ameliorations lasting several decades, such as between 1710 and 1738. The frequency of wet and fertile years in the Sahel belt as well as along the northern fringes of the Sahara increased, at least during some periods, for example between 1660 and 1690 - indicating a temporary shrinking and expansion of the desert 4. In other periods famines prevailed. A convincing coincidence with high-latitude features could not always be found. During some of the peak cold periods (around 1586, 1690-1700, 1770-80 and 1815-50), Arctic sea-ice not only blocked Iceland for many months, but reached the Färoes, where the sea-temperature fell about 4 deg C, and even Norway. This led to very severe consequences for agriculture, fisheries and the economy in general, especially in marginal climates such as Iceland, Scotland, Scandinavia and Finland. This was also true for mountainous regions like the Alps, where impressive records of climate and agricultural production from the Swiss Canton of Berne 43 have been evaluated for the critical years 1755-1797. These climatic anomalies may also have contributed to the socio-economic background of the French revolution.

The best documented major volcanic eruption (Tambora in Indonesia, 1815) was followed by two catastrophic years in many areas of the world. 1817 was the "year without summer" in the eastern U.S.A.; in central Europe the highest cereal prices between 1350 and 1950 were reached. These famine years initiated a mass emigration from western Germany to the United States. Simultaneously with the last glacier advance in the Alps around 1850, the weather-induced harvest failures after 1845 initiated the revolutions of 1848 (Austria, Germany, France, Netherlands). The most catastrophic famine occurred in Ireland after an outbreak of the weather-controlled potato blight.

In one province of Central Germany, cereal prices rose more than 500 per cent after the crop failure of 1770, and the population loss due to that famine amounted to nearly 100 000 or 6 per cent 44. Several studies of non-instrumental records between 1540 and 1700 indicated the great frequency of blocking anticyclones with their weather vagaries, as for example in the 1780's 3. Glacial advances in all mountains of the temperate and subpolar zone indicated a quite general cooling all over the northern hemisphere (which is more an exception than a rule). The simple estimate of a cooling 1-1.5 deg C (Table 2) looks quite innocuous to the non-specialist, but it can have very serious consequences. In marginal lands (including the wheat producing provinces of Canada) it means a reduction of the growing-season by several

weeks and a much greater frequency of the effects of adverse weather extremes such as harvest reductions are to be expected.

In spite of many careful local investigations, a comprehensive review of the circulation pattern and weather anomalies of these times is still lacking. Some evidence from North America suggests frequent blocking centres between 1815 and 1850 in the Gulf of Alaska 45. Quasi-stationary meridional troughs and ridges controlled the mid-latitude weather, producing all kinds of extreme climatic anomalies: droughts and inundations, high and low temperatures. The troughs also penetrated deeply into the tropics, triggering frequent extra-seasonal rains, together with droughts in other areas.

3.2 Initiation of a new Ice Age?

Since the disappearance of the Laurentide Ice (about 4 500 BP) several periods similar to the Little Ice Age have occurred, especially nearly simultaneously around 3 800 BP and 2 200 BP. In the Alps, 5 or 6 periods of glacial advances can be distinguished since about 9 000 BP, all of about the same intensity; similarly the recessions during the warm intervening periods apparently reached the same level 46 as now.

The total duration of the last glaciation outside the central area of the continental ice-domes was comparatively short; the valleys of the interior Alps were ice-free until 24 000 BP and after 14 000 BP, while around 18 000 BP the glaciers reached the suburbs of Munich and covered Zurich and Geneva. Similar dates are given for the marginal advance and retreat of the Scandinavian ice. There are many indications of abrupt climatic changes - on a time-scale of centuries or less - in past inter-glacials as well as at the beginning and end of each major glaciation. How can we imagine the initiation of a new ice age?

During the Little Ice Age, about 200 years ago, the ice-covered area of the high plateaus of central Baffin Island extended to 140 000 km², to be compared with 37 000 km² now 47. A temperature drop of 1-2 deg C was sufficient to displace the snow-line below the level of the plateau. Model computations 48 indicate that this situation may serve as the starting point for a new glaciation of the Laurentide Shield, expanding after some time to the Labrador highlands. The speed of this model evolution is rather slow, but this could easily be altered by varying some of the model parameters within their range of uncertainty. The cold interlude during the last inter-glacial (Section 2.3) reached a nearly full glacial development (Figure 1) apparently on a time-scale of the order of less than a thousand years.

At any rate, the transition from the present climate towards a large-scale glaciation - which should hardly be expected before the radiation minimum 7 000-13 000 years in the future - needs much more than 100 years before the ice expands beyond Baffin Island and adjacent areas of the Canadian Archipelago. This is also suggested by the fact that the cooling of the Little Ice Age, extending over 300 years, was not sufficient to expand the Baffin ice sheet much beyond the high plateaux. The critical area is Labrador, where a local cooling of 5-6 deg C, together with increased precipitation, is needed for a permanent snow-cover, which must in any case develop as the first stage of a glaciation.

Thus in a scenario of probable climatic evolution during the 21st century it is unnecessary to consider the evolution of a new ice-age. Only very special (and unpredictable) external conditions could trigger such an event: either a rapid decrease of the solar constant or a very large-scale Antarctic surge ($> 10^6 \text{ km}^3$ of ice), and in the latter case no historical example exists with a sufficient degree of certainty. The probability of such an evolution during the next 100 years remains almost certainly below 0.1 per cent. Volcanic eruption clusters much stronger than those during the last 500 years must have existed 49 at the beginning of the Pleistocene 2.5 million years ago or during the middle Miocene (about 12 million years ago). A recurrence of such extremely rare events known only in very remote times must have a very low probability 50. Nevertheless, the abrupt initiation of a new ice-age would have such a tremendous impact on all kinds of human activity that further investigations should be recommended.

4. Conclusions

Looking towards possible evolutions of our climate during the next century, the most simple assumption is that it will remain the same as during the last 50 years. But this period was by no means normal: the reference period 1931-60 was indeed one of the most abnormal periods of the last 500 years. Climatic history tells us that a normal climate only exists in a very broad sense, and that many climatic periods have existed that differ considerably from the present situation - much more so than might be inferred from a global temperature change of a few degrees Celsius. The possibility of a major man-made warming has fascinated many scientists mainly because serious consequences might result. For this situation a sober analysis of background facts is necessary.

In many discussions, the possible occurrence of a sudden cooling due to natural causes has been neglected. The probability of heavy volcanic eruptions, perhaps a cluster of them, with the intensity of Krakatoa (1883) or even Tambora (1815), can never be excluded. Indeed the very recent increase of seismic activity seems to indicate an active phase of tectonic motion of the large plates of the Earth's crust, correlated with increased volcanic activity along the oceanic rift system. A cluster of heavy explosive eruptions (similar to periods around 1690 or 1830) could suddenly initiate a marked period of cooling, possibly similar to the Little Ice Age. Assuming an irregular behaviour of fluctuations on the time-scale around a century 51 with successive peaks occurring at random, the risk of such an evolution during the next 100 years can be estimated to be somewhere, between 10 and 20 per cent. With increasing global warming, this risk may diminish gradually, but never disappear. Here the possible role of solar activity is neglected, since the available evidence of solar-weather relations is still conflicting and physical causes of the variations of the solar activity are little understood.

In contrast to the possible occurrence of major cooling due to natural causes, the probability of a man-induced future global warming is much greater and increases with time. Soon after the turn of the century, a level may possibly be reached that exceeds all warm periods of the last 1 000-1 200 years; the evidence from examples of past warm climates can only be used when taking into account the changes in the boundary conditions (ice extent, coastlines, vegetation changes etc.).

This is the more true for an eventual transition to an ice-free Arctic Ocean. If an increase of the virtual CO₂-level by a factor of 3 or 4 - assumed to be equivalent to an increase of the real CO₂ content towards 750-900 ppm - cannot be impeded, the probability of such a dramatic event rises rapidly. That this climatic pattern probably did not occur during the last 2.3 million years and certainly not during the last seven hundred thousand years, does not mean that it cannot happen in the future. Indeed, it has happened before for a period of at least 10 million years, i.e., much longer than the duration of the Pleistocene with its full sequence of glacials and interglacials, under purely natural conditions. The occurrence of such a climatic evolution, leading - after a series of catastrophic years of extremes - to such a nearly unimaginable climate, with a high degree of hemispheric asymmetry, would certainly affect the human race as a whole. It is the conviction of the author that this risk must be avoided even at very high costs.

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ENERGY AND CLIMATE

A REVIEW WITH EMPHASIS ON GLOBAL INTERACTIONS

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1. Introduction

This paper considers the interaction between energy and climate; an interaction which operates in both directions. The byproducts of the conversion of energy can influence climate, while, in the other direction, climate can influence the demand for and supply of energy. The former aspect has recently received increasing attention 1 - 3 as awareness of man's potential to alter the Earth's climate has developed and as observations of the changes already being made on a local scale have been reported 4.

The impact on climate of the production and use of energy can be on a local, regional or global scale. At the present time, no observed global climatic changes can be attributed to energy conversion but possible changes on this scale in the future are of concern. This paper describes scenarios for the future development of energy systems, based on considerations of energy demand and the sources of supply. These scenarios provide a background against which the potential impact of energy on climate can be discussed. The paper therefore emphasizes the impact on the global climate of three main energy sources (solar, nuclear and fossil fuels), which could undergo further development on a large scale during the next fifty years.

Though the major part of the paper discusses the potential impact on climate of energy systems and the implications of our present state of knowledge for energy policy decision-making, the impacts of climate on the supply of and demand for energy are also discussed. Lastly, the requirements for climate information, in order that the interactions between energy and climate may be more effectively assessed, are outlined.

2. Energy Systems

World primary energy consumption in 1975 was at an average rate of about 8 tera watts (TW) ($1 \text{ TW} = 10^{12} \text{ W}$). The share of oil and gas in this total was about

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5.3 TW, with oil from the Middle East amounting to nearly 1.4 TW. The existence, at present, of this essentially point source of energy supply is of significance when future energy systems are considered.

Growth in energy demand is stimulated by many factors. Predominant among these are the world population growth, the development of less advanced countries and continued industrialization in developed countries. The most important stimulus for energy growth in the future will probably result from efforts to reduce the differences between developed and developing countries. The present unequal distribution of energy consumption is illustrated in Figure 1.

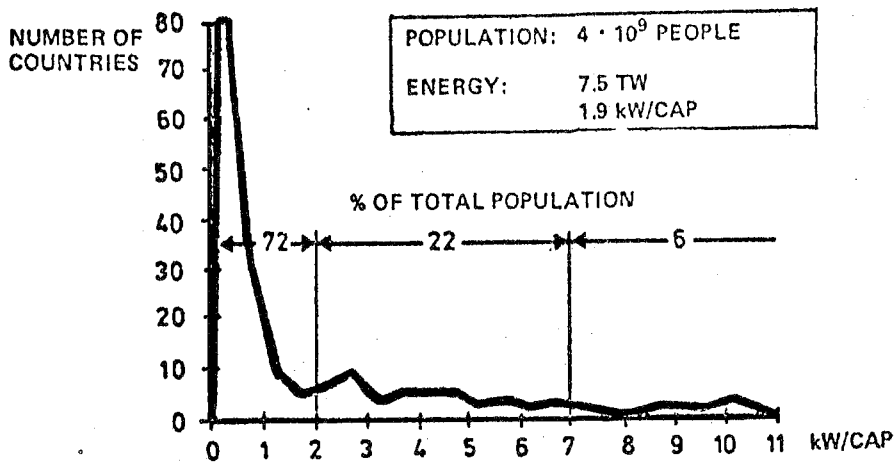


Figure 1: Energy consumption for the world in 1971 (Source: J.-P. Charpentier, IIASA).

IIASA is preparing for publication a detailed description of the scenarios for future energy demand that have been considered in its Energy Systems Programme. The scenarios are defined in terms of population, aggregate economic growth and primary and final energy demand for seven regions of the world. Population projections for these regions were taken from Keyfitz [5], who assumes a mere replacement level of fertility in the developing regions by 2015. The scenarios are based to a large degree on two recent energy studies: The Workshop on Alternative Energy Strategies [6] and the tenth World Energy Conference [7]. Two scenarios have been derived: a high economic growth (and energy demand) case and a low economic growth case. For the year 2030 the high and low scenarios give primary energy requirements of 40 TW and 25 TW respectively. That is, the order of magnitude of energy demand fifty years from the present is projected to be 25-40 TW, compared with about 8 TW now.

In addition to demand, it is necessary to consider supply of energy. Most of the present supply is from fossil fuels (coal, oil and gas) and in the future, in addition to these sources of energy, non-conventional fossil fuels such as secondary and tertiary oil recovery, high-cost low-grade coal, tar sands and oil shales must

be taken into account. A second supply source is nuclear energy conversion, which at present largely comes from the light water reactor but fission and fusion breeder reactors are potential future sources. Hydropower and localized renewable energy sources (biogas, wind, soft solar and tides, for example) represent supply options which, although important on local and regional scales, have been considered to make only small contributions to a global energy supply of 25-40 TW 8. A further energy supply source to be developed during the next fifty years is hard solar energy conversion, where the solar energy is converted to electricity, methanol, hydrogen or some other secondary energy carrier. (Note: Soft solar refers to decentralized solar systems such as roof collectors. Hard solar refers to large-scale centralized systems such as solar thermal electric conversion systems.)

Realistically one has to expect global energy supply systems that for almost any conceivable situation would consist of a mix of the above described sources. Indicative numbers are: 15 TW of fossil fuel supply, up to 8 TW of nuclear supply (for electricity or other secondary energy forms), 3 TW for wind, biomass and soft solar, up to 1 TW for hydropower and, possibly, up to a few TW from hard solar.

3. The impact of energy systems on climate

In a discussion of the interaction between energy systems and the climate system, with reference to a projected demand in the year 2030 of 25-40 TW, the impact on climate of the large-scale deployment of three energy supply sources (nuclear, fossil fuel and solar) must be considered. These energy systems influence climate through the ejection of waste heat, by changing concentrations of atmospheric constituents or by large-scale changes in the characteristics of the Earth's surface 9.

Climate is a complex system with many feedback mechanisms between the components. It is the potential of energy systems to interfere with natural climatic processes so as to produce global climatic changes that has received increasing attention. It should be emphasized, however, that it is not the possibility of a globally-averaged climatic change that is the central issue but rather the inevitable regional shifts in climatic patterns that would result from a perturbation of the climatic system.

4. The impact of waste heat on climate

Power stations (nuclear, fossil fuel and some solar) eject waste heat into the climate system. The heat is added as latent or sensible heat to the atmosphere or as sensible heat to a water body, from which it can enter the atmosphere. On a local scale it has already been observed that releases of waste heat influence climate through the formation of the urban heat island 4. Although, as pointed out earlier, the problem of regional shifts of climate patterns deserves emphasis, global averages are usually considered in discussions of the impact of waste heat. On a global basis the total amount of heat currently released by mankind's activities is only slightly more than one ten-thousandth of the solar energy absorbed at the surface 10. An extreme projection of 20 billion people with a per capita energy demand of 20 kW, would lead to a total heat release of about 0.5 per cent of the solar energy absorbed and could give rise to a surface temperature increase of 1 deg C,

if one considers the energy balance of the global system. However, energy consumption is not and will not be distributed evenly over the surface of the earth, and it is the concentration of waste heat in certain areas that has the potential to alter global climate patterns. This potential could be realized with a total waste heat release less than that in the extreme projection above. Flohn [11] estimates that natural climatogenic processes producing global-scale climatic changes involve an energy loss or gain of the order of 100-300 TW. It is feasible that man-made perturbations of this magnitude could produce global-scale climatic changes.

The maximum amount of electric power generated currently at a single thermal power station is about 3 000 MW and the atmospheric effects of heat dissipation rates are not serious problems [12]. However, concern has been expressed [12] about proposals to build power parks to generate 10 000-50 000 MW on a land area of 5 to 100 km². The meteorological effects of such large releases of heat are not known but can be estimated on the basis of comparable sources of heat and moisture, such as islands heated by solar radiation, urban-industrial complexes, forest fires, volcanic eruptions and others [13]. Man's energy production over areas up to 100 km² is sometimes of the order of magnitude or greater than that of natural production. It has been suggested that waste heat release from power parks would increase cloudiness and precipitation in the area and possibly act as a trigger for severe weather [12, 13]. It has been pointed out, however, that the energy transport in tropical cumulonimbus, or hot towers, has an order of magnitude of 100 000 W m⁻². Thus the dissipation of large amounts of waste heat in the tropics could have an energy density less than the natural processes. That is, relatively large amounts of anthropogenic heat releases are not necessarily larger than those of natural processes and, when properly managed, should not necessarily have a significant climatic impact. In contrast to the dissipation of waste heat in tropical areas, thermal and pollutant emissions in high-latitude, cold-winter conditions are problematic. In Canada, Alaska, the Soviet Union and Scandinavian countries, strong temperature inversions at the earth's surface in winter create serious problems, which influence decisions on the location of power plants. In Fairbanks, Alaska, for example, mid-winter conditions become extremely unpleasant due to polluted ice fog at temperatures below -35 deg C, with the ice coming mainly from the very small thermal power station, and being trapped by the inversion.

The impact of waste heat on global climate has been studied using numerical models of the atmospheric circulation. The formulation of these models and their application in the study of human impacts on climate are discussed in the overview papers at this Conference by Gates, Mason and Marchuk. General circulation models (GCMs) are recognized as being the best tool available at the present time for investigating the global impacts of perturbations such as waste heat. It should be recognized however that the GCMs do have shortcomings which must be taken into account when the results of experiments are interpreted [14]. In particular the absence of a coupled ocean circulation, poor treatment of clouds, hydrological and other processes, notably on scales smaller than the spatial grid used in the calculations, are seen as shortcomings. The methodological problems of determining the significance of results of experiments have also been extensively discussed [15].

Washington [16] used the GCM developed at the U.S. National Center for Atmospheric Research (NCAR) to investigate the response of the model atmosphere to an addition of 24 W m⁻² over all continental and ice regions. Results showed a 1-2 deg C

increase in global average surface temperature with an 8 deg C increase over Siberia and northern Canada. A more realistic input of heat was used in further studies 17 which assumed a per capita energy usage of 15 kW and a population of 20 billion. The energy was released according to present population density distribution. It was concluded, however, that the thermal pollution effects were no greater than the inherent noise level of the model. In a further experiment with the NCAR GCM, waste heat was added to an area extending from the Atlantic seaboard of the U.S. to the Great Lakes and to Florida 18. It was assumed that energy consumption in that area was equal to that now consumed in Manhattan Island (90 W m^{-2}). Temperature differences of as much as 12 deg C were observed in the vicinity of the anomalous heating but the authors concluded that the heating had little effect above the surface layer and downwind from the source region.

Within the IIASA Energy Systems Programme and in co-operation with the U.K. Meteorological Office a series of experiments has been carried out, with the GCM developed by the Meteorological Office 19 in order to investigate the sensitivity of the atmospheric circulation to waste heat release from point sources in ocean areas. The principal reason for considering such point sources was that with a waste heat input of 150-300 TW, a significant response of the simulated atmospheric circulation was only likely if the input was concentrated in a small area. Earlier experiments 17 had indicated that when 300 TW was input over all of the continental area significant effects could not be detected.

One may or may not give some technological meaning to such point sources. The concept of energy islands was considered by Häfele 20 in terms of the necessity of "embedding" energy systems within the atmosphere, hydrosphere, ecosphere and sociosphere. As mentioned above, when large amounts of waste heat are released into the atmosphere a point can be reached where the man-made power density equals the natural power density and the atmospheric conditions could therefore constrain the development of energy systems. Häfele 20 considered the embedding of energy systems into the hydrosphere in terms, among other things, of the amount of water available in continental runoff for the disposal of waste heat. A value of $35 \times 10^3 \text{ km}^3 \text{ y}^{-1}$ is quoted for total runoff. If all the runoff were heated by 5 deg C, 0.25 W m^{-2} of waste heat could be dumped, which, given the total continental area, means that about 27 TW of waste heat could be disposed of. These numbers merely illustrate the order of magnitude of the constraint of the hydrosphere. The embedding of energy systems in the ecosphere and sociosphere involves consideration of pollution and the concept of risk respectively.

Five experiments have been made with the Meteorological Office GCM in order to examine the impacts of point sources of waste heat input 21 - 23. Figure 2 shows the locations of the heat input that have been considered. The Table below shows the combinations of point sources and heat input used in each experiment.

The impact of 150 TW or 300 TW of waste heat was investigated. These high values for energy input were used since the earlier experiments of Washington 17 had also used 300 TW and a basis for intercomparison was therefore available. It is also acknowledged that the input into models of large perturbations is required if a significant response is to be seen in the simulated global circulation. The realistic simulation of such heat input would involve the use of a coupled atmosphere-ocean model so that the heat would be added to the ocean, some would be transported

by ocean currents and heat would be added to the atmosphere as both sensible and latent heat. In four of the GCM experiments, heat was added only as sensible heat to the lowest layer of the atmosphere, while in the fifth experiment the heat was added to a 10 m deep ocean box simulated beneath each area of waste heat input.

Table

The Combination of Areas and Amounts of Heat Input in Five GCM Sensitivity Experiments (Locations A, B and C shown in Figure 2)

EX	Area	Heat Input	Remarks
01	A & C	$1.5 \times 10^{14} \text{ W}$ at each	Total heat input $3 \times 10^{14} \text{ W}$
02	B & C	$1.5 \times 10^{14} \text{ W}$ at each	Total heat input $3 \times 10^{14} \text{ W}$
03	A only	$1.5 \times 10^{14} \text{ W}$	Total heat input $1.5 \times 10^{14} \text{ W}$
04	A & C	$.75 \times 10^{14} \text{ W}$ at each	Total heat input $1.5 \times 10^{14} \text{ W}$
05	A & C	$1.5 \times 10^{14} \text{ W}$ at each	Heat added to 'ocean box' below each area rather than directly to atmosphere

The results of the experiments have been described in detail elsewhere 21 - 24. Figure 3 shows the differences in sea-level pressure between the first experiment and the average of three control cases (January cases, averages of days 41-80). There are large coherent areas of sea-level pressure change not just over the areas of heat input but elsewhere in the hemisphere. It is found, for example, that the response in the vicinity of the Atlantic heat input is similar in other experiments and this gives confidence in interpretation of the response as significant.

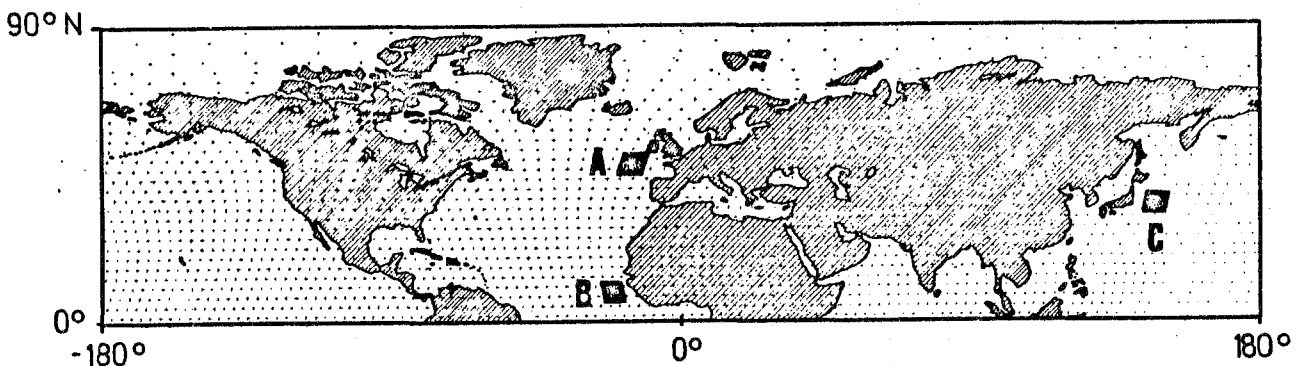


Figure 2: Location of point sources of waste heat input used in GCM experiments 21 - 23.

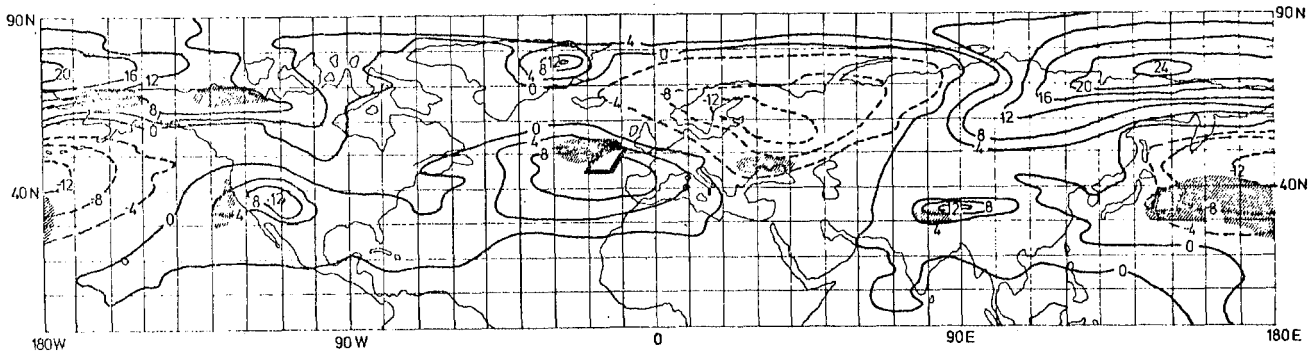


Figure 3: Difference in 40-day mean sea-level pressure in EX01 and the average of the three control integrations. Shaded areas indicate where "signal-to-noise" ratio is greater than 5.0. Units: mb. 21.

It is found that the response of the simulated atmospheric circulation to the input of large amounts of waste heat at point sources is not just in the area of input. The response varies according to the location, amount and method of heat input. As mentioned above, the results of GCM experiments must be viewed recognizing model shortcomings. It must also be stressed that the amounts of heat used so far in model studies have been unrealistically large in order to ensure a distinct signal. Input of more realistic amounts of waste heat is likely only to impact local or regional climate, as described above, rather than global climate.

Marchetti and Häfele 25 have suggested that the release of large amounts of waste heat in ocean areas, if done "intelligently" (for example, by making use of deep, cold ocean water), would have no global climatic impact. The release of large amounts of waste heat into the tropical atmosphere, where hot towers are observed to transport energy of the order of several hundred TW, must also be considered. Since such phenomena occur on scales smaller than the grid used in present GCMs, this possibility cannot be investigated with present tools.

Results of GCM experiments suggest that waste heat is a "non problem" on a global scale, in that it is unlikely to perturb the global average climatic state in the foreseeable future. Only when extremely large amounts of heat input (of the order of several hundred TW) were inserted in special modes, such as point sources, could significant changes in the atmospheric circulation be determined. It is notable that these changes were not only directly over the area of heat input. However, with an energy consumption level of 25-40 TW there appears to be little or no ground for world-wide concern regarding the climatic impact of waste heat release.

5. The impact of fossil fuel energy conversion on climate

Fossil fuel energy conversion produces, in addition to waste heat, certain gaseous and particulate substances which can interact significantly with the climate system. The release of carbon dioxide by fossil fuel consumption has received particular attention recently in view of the physical properties of the gas and its

observed build-up in the atmosphere. The overview papers by Bolin and by Munn and Machta describe these aspects in more detail. A doubling of the atmospheric concentration of CO₂, according to state-of-the-art climate models, would lead to an increase of 1.5 deg C to 3.0 deg C on the global average surface temperature. Of course these numbers could be high or low because of feedbacks not accounted for or incorrectly incorporated in present models. Also, as discussed above, regional changes in climate (and in particular of precipitation) are of more significance than global average surface temperature changes and model and observational studies have shown that polar areas are more sensitive to a global temperature increase than other latitudes [26, 27]. The release of particulate material has also been considered [28] and some interest has focussed on releases of sulphur and nitrogen compounds, which will probably not have as large an impact as the above substances [29, 30].

Particles are both directly produced as smoke or soot and indirectly from gases as in the case of sulphates and hydrocarbons. Observational evidence for changes in particle loading of the atmosphere [31, 32] show an increase in loading during the past century, but it is not clear whether this increase is a regional or global scale phenomenon [31]. The interaction of particles with radiation and thus their impact on climate depends on complicated absorption and backscatter characteristics of the particles and on surface and cloud conditions. It seems that most anthropogenic particles exist over land where they are formed, and are sufficiently absorbing to cause a warming of the earth-atmosphere system [10]. However, there is no quantitative evaluation of the role of particles at the present time, due to lack of observed data on the nature and distributions of the particles and of appropriate models.

Particles can have further impacts on the condensation/precipitation process and on the albedo of clouds [10] but the climatic consequences of these have not been considered in detail. As Mitchell [31] has pointed out, if particle loading is non-uniform over the surface of the Earth, geographical inequalities in the radiative effects could induce large-scale atmospheric circulation changes, and the implications of this should be studied with three-dimensional GCMs.

6. The impact of carbon dioxide on climate - implications for energy strategies

In order to assess the future atmospheric CO₂ concentration and its implications, three models are required. An energy model is used to estimate the future use of fossil fuels, and thus the input of fossil fuel CO₂ into the atmosphere. The proportion of CO₂ that remains in the atmosphere is then given by a model of the carbon cycle, as described in the overview paper by Bolin; such models consider the reservoirs of carbon and the transfers between them. Lastly, the effects of the increased atmospheric CO₂ concentration can be assessed using a climate model. At the present time, uncertainties must be attached to the results of each of these models, as discussed in more detail in the overview papers by Munn and Machta, Mason, Gates, Marchuk and Bolin. For example, in the use of carbon models much uncertainty has arisen regarding the role of the biota, i.e., whether it has been and is a source or a sink for atmospheric CO₂. In the use of climate models the role of feedback mechanisms, such as the cloudiness-temperature interaction, have to be included. Because of uncertainties, the future use of fossil fuels and the implications thereof cannot be reliably predicted. Nevertheless the model results can currently be used to assess the magnitude of the problem. An

example of the combined use of an energy model, a carbon model and the results of a climate model is given in a study by Niehaus and Williams 33. The model of the carbon cycle 34, 35 simulates the exchange of carbon and radiocarbon between eight reservoirs. The global average surface temperature response to the increasing atmospheric CO₂ concentration was assumed from the study of Manabe and Wetherald 36. Derivation of the energy strategies combined the results of two models of energy demand 37, 38.

Figure 4 shows two hypothetical energy strategies for the period up to 2050. In Figure 4a the energy consumption reaches a level of 30 TW by the year 2050, the use of fossil fuels peaks at around the year 2000 and energy is largely supplied after that date by solar and nuclear sources. In the second strategy, Figure 4b, the energy consumption reaches 50 TW with the entire demand being satisfied by fossil fuels. Figure 5 illustrates the atmospheric CO₂ concentrations given by the carbon model for these strategies, together with CO₂ emissions resulting from the strategies and estimates of the resulting global average surface temperature change. For the 30 TW nuclear and solar strategy the emissions of CO₂ peak around the year 2000. In this case, the atmospheric CO₂ concentration reaches a maximum of 400 parts per million (ppm) by volume in about 2020 and the resulting change in mean surface temperature is less than 1 deg C. On the other hand, if energy consumption reaches 50 TW by 2050 and only fossil fuels are used to supply this energy then the emissions of CO₂ increase until 2050, giving an atmospheric CO₂ concentration at that time of 800 ppm, implying a mean surface temperature increase of about 4 deg C.

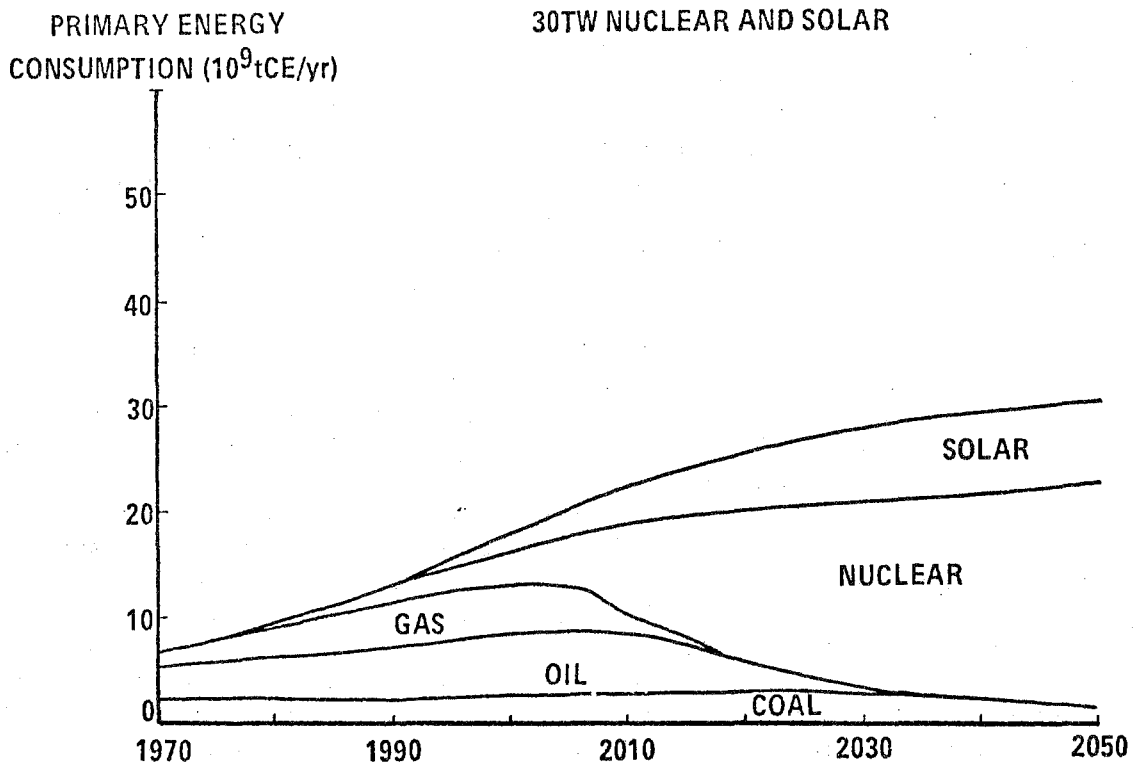


Figure 4a: Energy strategy for the period 1970-2050, maximum consumption of 30 TW with large solar and nuclear contribution 33.

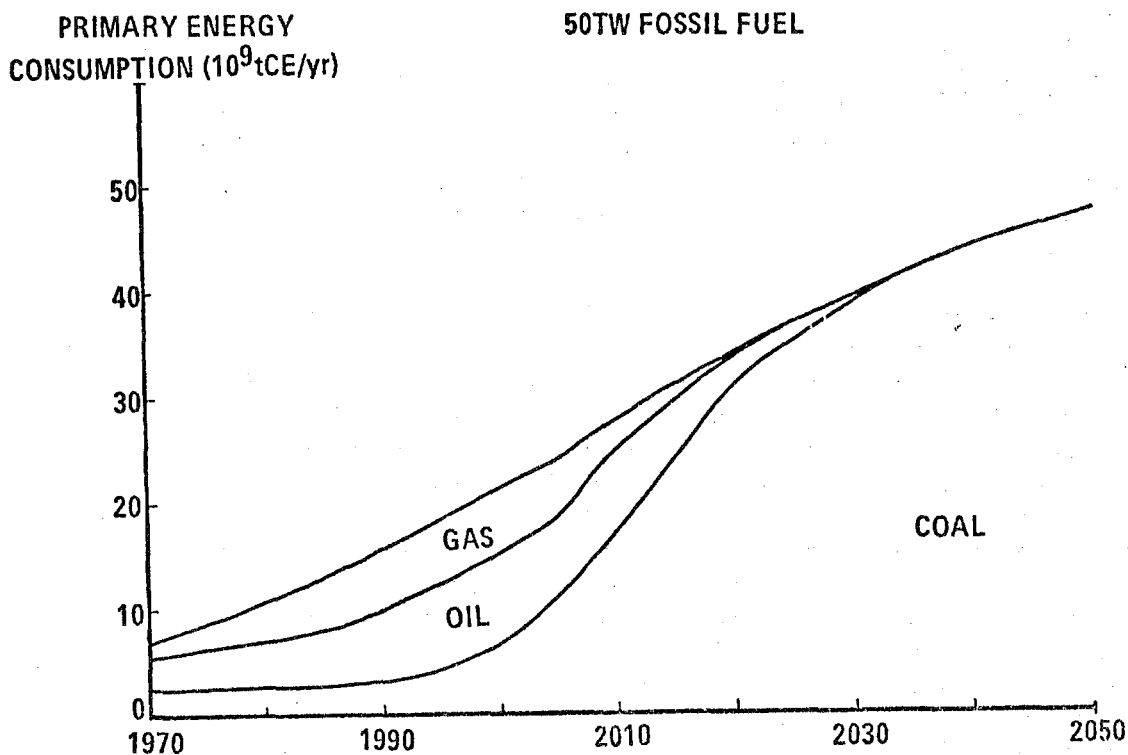


Figure 4b: Energy strategy for the period 1970-2050, maximum consumption of 50 TW with only fossil fuel supply 33.

As stated above, the results of the models have many limitations and cannot be taken as reliable predictions but they do show that, depending on the energy strategy followed, the climatic impact due to fossil fuel CO₂ would be small (<1 deg C by 2050, as given by a simple climate model) or large (about 4 deg C by 2050). An important point to be considered in this regard is that the dynamics of substitution of primary energy carriers, which depend on economic and technical constraints, has a time scale of decades 39. That is, it is not easy to change quickly from one energy strategy to another.

In reality the flexibility implied in the two energy strategies illustrated in Figure 4 cannot be assumed. More realistic strategy branching is illustrated in Figure 6, which shows an opportunity tree for energy strategies. In 1978, non-exclusive opportunities exist for three energy branches. If the strategy is towards satisfying an energy demand of 24 TW by the year 2030 it is possible to use conventional fuels. When the conventional sources are not enough to satisfy the demand, the timing of this point is somewhat arbitrary. Either non-conventional fossil fuels can be used or endowments must be created, that is, capital can be used instead of consumptive uses of resources 40. If non-conventional fossil fuels are used then a point might be reached at which CO₂ becomes a problem, in which case the use of capital instead of resources must be made. In the case of strategy to satisfy an energy demand of 40 TW, the decision to use unconventional fossil fuels or capital in the form of endowments is made earlier and again, if the CO₂ becomes a problem, the switch from unconventional fossil fuels to the use of capital instead of resources must be made. This opportunity tree for energy strategies shows that the 24 TW and 40 TW paths are not so different in terms of the strategy questions that have to be addressed, but rather in their timing. It also illustrates the possibility of

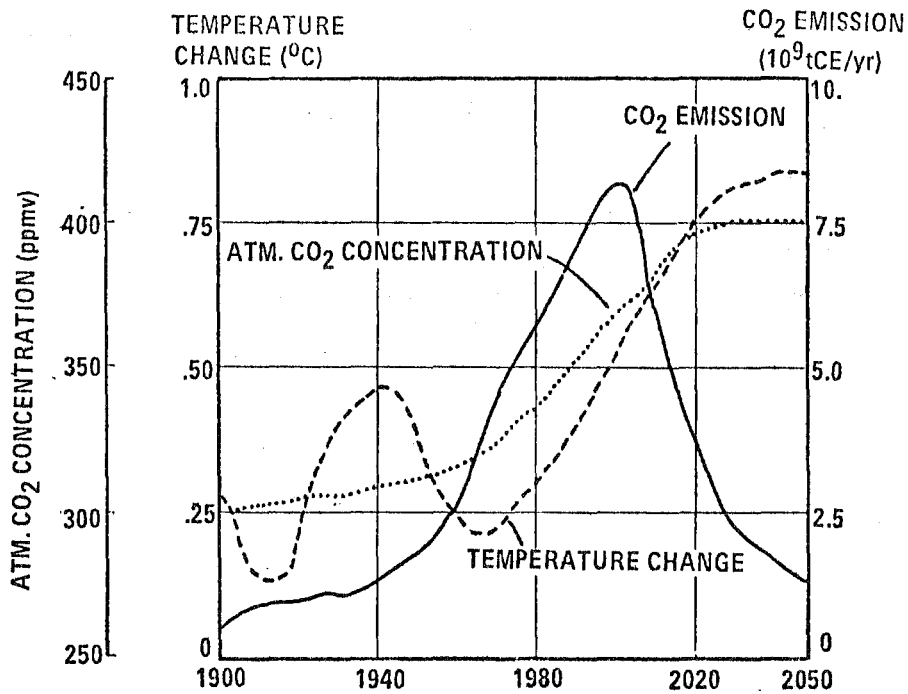


Figure 5a: CO₂ emissions, atmospheric CO₂ concentration and temperature change for strategy in Figure 4a 33

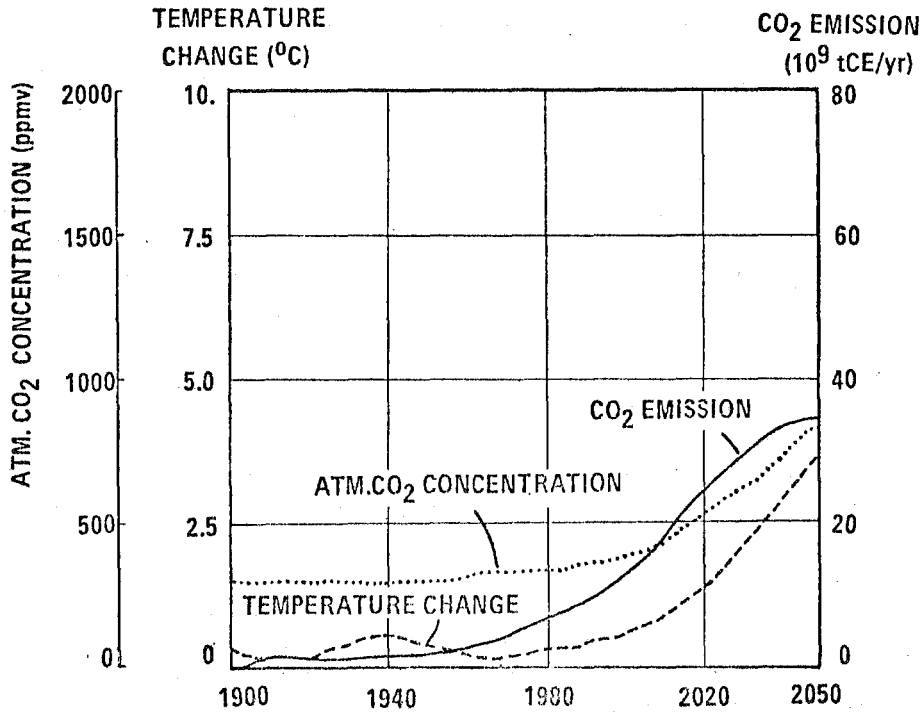


Figure 5b: CO₂ emissions, atmospheric CO₂ concentration and temperature change for strategy in Figure 4b 33.

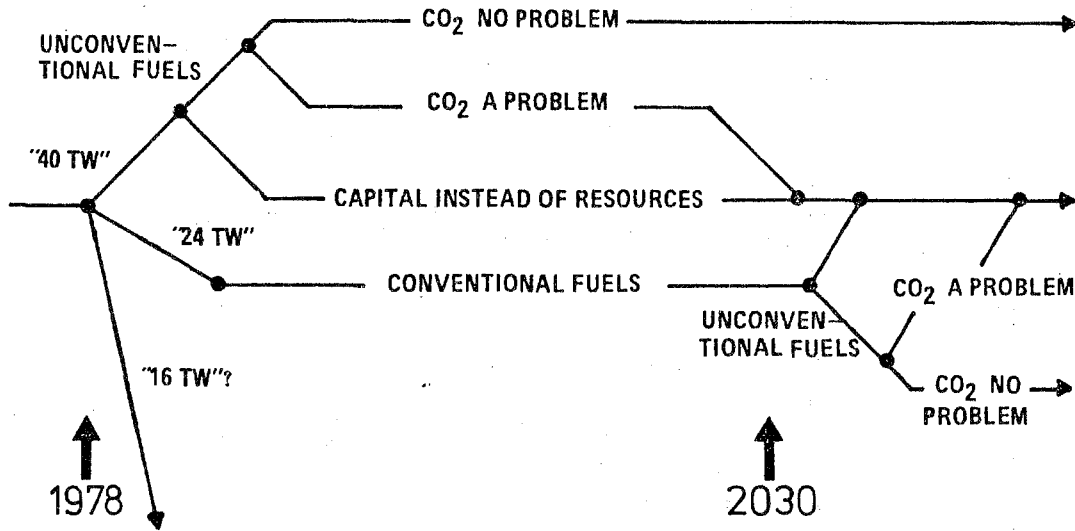


Figure 6: An opportunity tree for energy strategies.

switching from the resource branches to the endowment branches. Such considerations illustrate the large-scale technological and strategic implications of the CO₂ problem.

7. The impact of large-scale conversion of solar energy on climate

If it is assumed that solar energy conversion systems supply the majority of the required energy then it can be considered that the systems that have the potential to supply about 30 TW are solar thermal electric conversion (STEC), photovoltaic (PV), ocean thermal electric conversion (OTEC), and solar satellite power (SSP) systems. The impact on climate of the latter system has not yet been evaluated. Other solar energy conversion systems can locally be used for energy supply (e.g., wind and wave power systems) but are not expected to contribute largely to the global energy requirement [40] and therefore cannot be expected to have a global climatic impact.

The possible climatic impact of large-scale deployment of solar energy systems has received little attention. A workshop was held at IIASA in 1976 [41], which discussed the physical characteristics of the systems, assessed their impact on boundary conditions of the climate system and discussed the climatic implications of such impacts.

Large scale deployment of STEC systems would lead to regional changes in the surface heat balance, surface roughness and hydrological characteristics. Jäger et al. [42], for example, have discussed the surface energy balance changes due to STEC systems. Simple estimates [43] show that, in the absence of a STEC plant, short-wave radiation, long-wave radiation and sensible plus latent heat leaving the surface are 30 per cent, 35 per cent and 35 per cent respectively, of the total incident radiation. In the presence of a STEC plant with a 40 per cent ground cover ratio, at which 17 per cent of the sunlight reaching the heliostats is converted to electricity, the shortwave radiation leaving the surface is 14-23 per cent, the

total of the long-wave radiation and sensible plus latent heat leaving the surface is about the same as in the absence of the STEC plant (i.e., about 70 per cent). However, in the presence of the STEC plant 49-20 per cent of the total incident direct radiation is released as waste heat at cooling towers, the long-wave radiation leaving the surface is 10-25 per cent. The ranges refer to seasonal extremes, the first number is for winter, the second for summer. That is, the STEC systems do not really change the magnitude of the net heat flow from the surface to the atmosphere but the mechanism of transfer is changed; the significantly lower heat release from the surface is compensated by a release of waste heat from cooling towers upon energy conversion. In this respect some impacts of STEC systems on climate can be evaluated in the same way as the potential impact of waste heat from fossil fuel or nuclear power plants.

Since heliostats are several metres tall, the arrays would influence the surface roughness. A few GCM studies have been made of the impact of a change in roughness but no specific studies of the impact of STEC (or PV) systems have been carried out. Similarly, no specific studies of the potential climatic impact of large-scale changes in hydrological characteristics due to these systems have been made, but model and observational studies indicate that large scale changes in surface wetness can significantly influence climate 44, 45, 46. The potential impact of PV systems is generally considered to be similar to that of STEC systems.

OTEC systems use the vertical temperature gradient in the ocean to generate electricity. Even harvesting a small fraction of 30 TW could cause major impacts which would be due to temperature anomalies caused by reducing the surface temperature and diverting the flow pattern through the discharge of extremely large volumes of cold, deep ocean water required for cooling purposes. Again, both observational and model studies have indicated that sea-surface temperature anomalies can influence climate 47, 48, 49. Further impacts of OTEC systems could arise because of the upwelling of water, through albedo changes, for example, but these have not been investigated in detail 41, 50.

8. Implications for energy policy of the climatic constraint

At the present time there are many uncertainties about the specific climate impacts of large scale deployment of any of the major energy supply sources. It seems likely, however, that the global impacts of waste heat and changes in surface conditions will be felt at a more distant point in time than those from changes in concentrations of carbon dioxide and certain other infrared-absorbing gases. In recent years, most concern has been centred on the CO₂ question. The question is, whether present knowledge of the carbon cycle, the climate system and energy strategies justifies changes of energy policy. The IIASA Workshop on Carbon Dioxide, Climate and Society 51 discussed this question. It was concluded, firstly, that mankind needs and can afford a period of between 5 and 10 years for vigorous research and planning to narrow uncertainties sufficiently to be able to decide whether a major change in energy policy is called for.

With reference to the state of knowledge on the CO₂ problem and all of the uncertainties, participants at the IIASA Workshop formulated a number of policy statements, which will be discussed below and which can, to a large extent, be taken

as a general statement on the interaction between energy policy and climate research at the present.

Firstly, it was stated that since quantitative estimates on the rates of increase of CO₂ (and other infrared radiation absorbing molecules) in the atmosphere and resulting global and regional climatic changes are not only uncertain but likely to remain so for most of the next decade, it is premature to implement at this time policy measures requiring the reduction of the use of coal and other fossil fuels. Present knowledge justifies comprehensive study of many alternative energy supply systems but does not yet warrant a policy of curtailment of fossil fuel use.

A second point is, however, that policies that emphasize the use of coal are at present equally unjustified. Such policy decisions can become difficult and very costly to reverse and it is most important to maintain flexibility in energy supply policies at this time. With regard to this call for flexibility, the opportunity tree in Figure 6 demonstrates the strategic importance of the endowment branches, i.e., the opportunity to generate large amounts of secondary clean energy in large capital-intensive central installations.

Thirdly, it is clear that climatological impact assessments of escalating energy use must be performed in greater depth than in the past.

The fourth point discussed the possibilities of energy supply systems that allow ready environmental amelioration. Such systems would have to be either non-polluting (or very nearly so) or lead to environmental effects that can be easily mitigated. There are several possible systems which can satisfy these conditions, e.g., a solar or hydroelectric hydrogen system or an energy supply fuelled largely by synthetic methanol manufactured at energy "islands" using nuclear (breeder) or hard solar energy supply (endowments). Very highly decentralized solar energy supply systems could also be considered to satisfy these conditions but the participants felt that these are unlikely to maintain the global economy at a satisfactory level. Systems employing a short-term recycling of carbon through the atmosphere can also be considered. For example, the use of biomass as a fuel is a possibility. Stripping CO₂ from exhaust stack systems and even from the atmosphere itself ^[52] is not in principle infeasible and the manufacture of methane or methanol from the carbon thus obtained would be an effective 'recycling' system. The carbon could also be stored in the living biomass or in the deep ocean ^[53].

9. The impact of climate on energy supply and demand

Figure 7, from Critchfield ^[54] illustrates the relationship between climate and energy policy considerations, pointing out the role of climate in affecting energy supply and demand in contrast to the impact of energy systems on climate, which has been considered in earlier sections of this paper. In terms of the impact of climate on energy supply, as indicated in Figure 7, climate can influence research and exploration for energy sources. For example, exploratory drilling for oil in the Gulf of Mexico entails climatic problems quite different from those on the North Slope of Alaska ^[54]. Selection of sites for power stations also requires climatic consideration. The roles of different climatic variables are of particular significance in the case of solar, wind and hydropower sources. For this reason, programmes

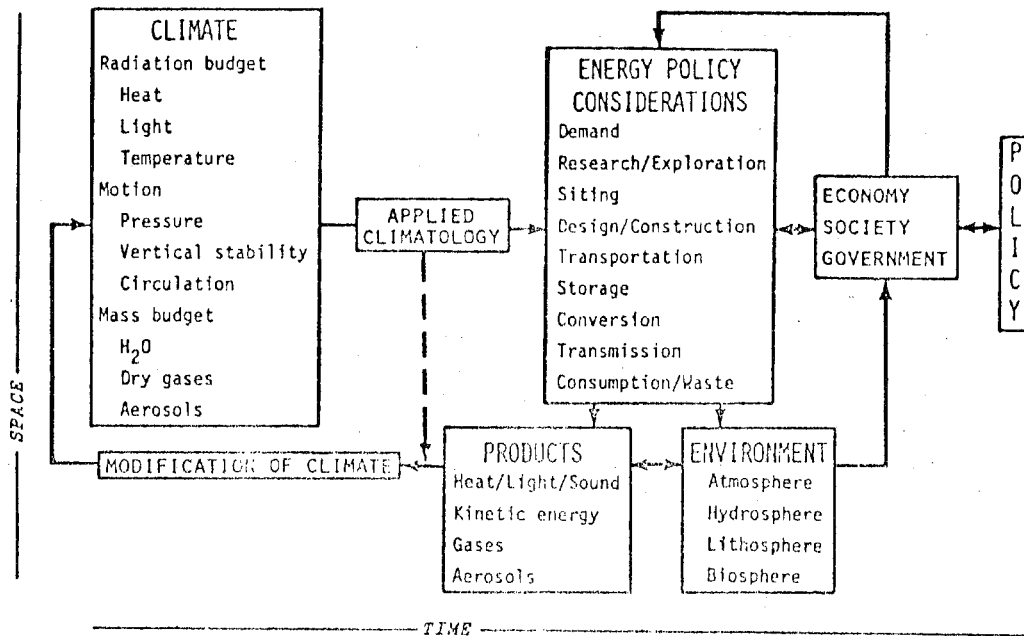


Figure 7: A model of climatology in a comprehensive energy policy ^[54].

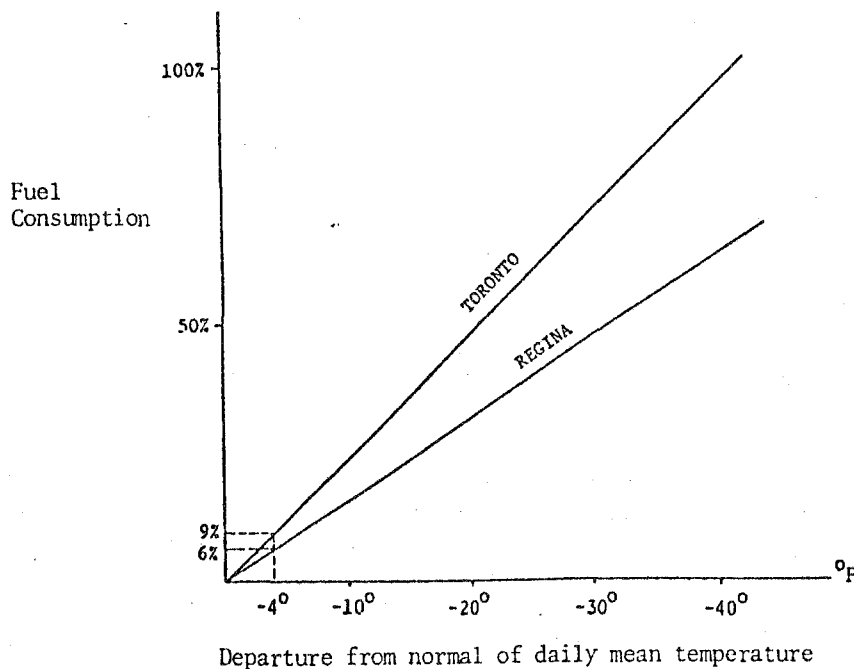
such as the U.S. National Insolation Resource Assessment Programme are established ^[55] in order to collect, record and archive climate data useful to the forecaster and researcher. Local climate also influences the method, materials, timing and costs of construction of energy supply facilities and also the transportation of energy (e.g., routing of colliers and tankers, highway and railway maintenance).

The impact of climatic variation on supply is mainly through the impact on renewable resources such as wind and solar systems, although transportation of other energy sources can be affected by anomalous climatic conditions. Droughts have been noted to influence hydropower supply. For example, the drought in the north-east U.S. during the period 1961-66 reduced flow rates of rivers and reservoir levels. New York City reservoir levels were reduced to 40 per cent of their capacity in 1965 ^[56]. During abnormally wet periods significant surpluses of hydroelectric power may be temporarily available.

As far as the impact of climatic variability on demand is concerned, it has been shown, for the U.S. at least, that the increasing use of air conditioning and electric heating in homes has increased the sensitivity of energy demand to temperature changes. McQuigg ^[57] showed that there was a noticeable increase in electricity demand as a function of increasing temperature because of air conditioning. Mitchell et al. ^[58] have computed the seasonal total heating degree-days for each state of the U.S. for each of 42 heating seasons from 1931-32 to 1972-73. The study allowed an estimate of climate influences on heating-fuel demand. Results showed that in one year out of 100 years one should expect a national total demand for heating fuel to exceed the long-term average demand (for constant economy) by as much as 10 per cent. Similarly the demand can be expected to exceed its average value by at least 3.6 per cent on an average of one heating season in five. Of course, when one part

of the continent is colder than average it is not unusual for other sections to be warmer than average. The probable extreme deviations are larger when regions are considered, especially in the southern and Pacific states of the U.S. For example, for the South Atlantic states, in one year out of 100 years one should expect a total demand for heating fuel to exceed its long-term average demand by 20.4 per cent. To the extent that fuels are not readily distributed from one part of this country to another these inequalities are of great significance.

Examining the record of winter accumulations of heating degree days it was found 56 that the greatest accumulation occurred over the northern United States and Canada during the winter of 1935-36. Figure 8 shows an estimate of the percentage increase in heating fuel consumption by temperature for Toronto and Regina for the winter season. On the basis of this figure it has been estimated that large areas of the northern United States and Canada would have had an increased fuel consumption of 50 per cent or more in February 1936.



Source: Environment Canada, Atmospheric Environment Service, Toronto - based on heating-degree-day normals.

Figure 8: Estimated percent increase in heating fuel consumption by temperature for Toronto and Regina (for period January, February, March) 56.

One further interaction between climate, energy demand and supply is in the field of weather and climate forecasting. With regard to the sensitivity of energy use to weather influences, the value of a forecast of an extreme event, based on climatological data has been pointed out 59. It must also be noted that there is

a systematic and deliberate attempt by engineers to design excess capacity into systems to allow for climate-induced problems. This adds to the capital cost, especially in hydropower systems. An example of the interaction between the forecasting of climate events and the setting up of reserve capacity can be cited with reference to natural gas systems, where it has been shown that small temperature forecast errors cause very large reserves of natural gas to be required by moderate-sized cities to protect against optimistic errors during cold weather 60. There is clearly a need for adequate climatological information for the design of the energy systems, and also for the effective incorporation of this information. The implications of this are far-reaching. Thus for example, if a utility company installs a large amount of hydropower and then has a major surplus of energy production during a period of high runoff, decisions concerning base-load installed capacity (using other sources such as nuclear and fossil fuel power) and export policy to outside purchasers are greatly influenced. There is an obvious link between climate and capital investment, which must be optimized.

As illustrated in Figure 7 there are a large number of interactions between the climate system and energy systems. Many correlations between the two systems have been found but much work is still required. In particular an adequate theory of existing climate and an ability to predict future climatic variability are required. Until these are available much more could be gained from new or revised models for extrapolation, correlation and probability analysis 54.

10. Concluding remarks

The main points to be drawn from this review of energy and climate interactions are as follows:

- (a) Energy and climate interactions are in both directions: the byproducts of the conversion of energy can influence climate, while, in the other direction, climate can influence the demand for and supply of energy.
- (b) Detailed considerations of energy demand suggest that of the order of 25-40 TW of energy will be required in the year 2030.
- (c) To supply energy to satisfy this magnitude of demand, three large-scale sources are available: solar, nuclear and fossil fuels. Realistically one can expect a combination of these sources to supply the total energy requirement.
- (d) Each of the sources can influence the climatic system: by the emission of waste heat, by changing concentrations of atmospheric constituents, or by changing surface conditions.
- (e) Model experiments suggest that emissions of waste heat would have to be extremely large (of order 100 TW) to perturb the global average climatic state. However, waste heat can be handled intelligently or non-intelligently as far as the engineering systems are concerned and thus the climatic impact could be diminished or amplified. Likewise, changes in surface characteristics, such as albedo, roughness or wet-

ness, would have to be on a large scale to influence global climate. This is not to say that such perturbations due to energy systems would not influence climate on a local or regional scale.

- (f) The impact of increasing atmospheric CO₂ concentrations is perceived as the greatest risk at the present time. However, uncertainties in our knowledge of the carbon cycle and of the climate system are so large that we certainly cannot predict the consequences of increasing use of fossil fuels and a prudent energy policy would maintain flexibility at the present time while a period of 5-10 years is devoted to intensive research. Policies that actively encourage or discourage the use of fossil fuels are not justified at the present.
- (g) The impact of climate on energy supply can be considered in terms of the long-term assessment of the solar and hydropower resource. Climate will also influence factors in energy supply such as exploration (for oil in particular), choice of site for power plants, design and construction, transportation and storage. Climatic variability will also influence supply, particularly of the renewable resources.
- (h) The impact of climatic variability on demand is mainly through the effect of temperature changes on heating or air-conditioning requirements. The sensitivity is quite large. For the U.S. as a whole a variability of 10 per cent in seasonal requirements has been attributed to climatic variability, but regionally the requirements vary more.
- (i) In order to devise energy policies that take into account the climatic constraints, more detailed information on the impacts will be required - in particular, model results showing regional changes to be expected from different perturbations and scenarios of possible future climatic states. In this regard it is clear that major uncertainties still exist regarding the many feedbacks within the climatic system and thus it appears that even basic theoretical research is required in order that prudent energy policies, in which energy-climate interactions are considered, can be devised and used.

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CLIMATE VARIABILITY AND THE DESIGN
AND OPERATION OF WATER RESOURCE SYSTEMS

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1. Introduction

Climatic variability is important for the design and operation of water resource systems, because social benefits derived from these systems are direct functions of the reliability of system operations. This in turn depends on a proper understanding of the nature of climatic variability. Historically, water resource systems have been designed and operated on the assumption that future climatic variations might be expected to be similar to those observed within the past 100 or at most 200 years. This historical approach has worked reasonably well and is likely to continue unless there is some clear way to use information not presently being used. Therefore, it seems worthwhile to examine the way in which climatic information is used in water resources management, to consider what impact this has on society, and to consider what might be done differently in the future if the appropriate climatic studies were undertaken.

This paper begins by considering the nature of streamflow variability, and the way planners and engineers account for its effect. This includes a description of how stochastic hydrologic models have been used and the role they are likely to play in the future. Because reservoirs are essential tools in controlling the effects of climatic variability, the paper considers the relationship between storage, demand for water, and the risk of failing to meet water demands from a given reservoir.

The paper briefly reviews the importance of water resources variability for regions with different hydrologic and economic conditions. Economic, institutional, and legal issues are considered.

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Improved use of climatic information in water resources will involve an improved understanding of the relationships between climatic variables and water resource variables. This is most important in arid areas where the effects of climatic variability on the hydrologic cycle are greatly magnified. What is needed are improved climatic transfer functions for relating climatic variables and water resource variables. The paper considers three approaches to the development of these transfer functions: a statistical approach, an analytical approach, and a numerical approach. Suggestions for future climatic studies to enhance each approach are also offered.

2. Water resources variability and its impacts on society

Measurement of streamflow in rivers of the world is limited to a rather short period of recent history. This means that the long-term behaviour of wet and dry periods of streamflow cannot be known with great reliability. Nevertheless, practical water resources problems focus on streamflow variations that might be expected in the relatively near future, or, within the next 100 or at most 200 years. It is conventionally assumed that this future period will experience the same characteristics of climatic and natural hydrologic variations as was experienced for the last 100 to 200 years. (Later other approaches will be discussed.)

Streamflow variations throughout the world during the past 150 years were analysed by Yevjevich 1, 2, 3. Two large samples of annual river flow data, one on a global and the other on a continental sampling scale, were studied. The global data sample was from 140 river gauging stations distributed throughout the world and included records ranging in length from 40 years to 150 years. Six of the stations had records longer than 100 years; the average was 55 years. The continental streamflow sample was from 446 stations in the western North American Continent. Yevjevich applied techniques of correlation analysis and spectral analysis. He concluded that the results of his study "may give some comfort to those in practical fields of endeavour, who plan systems and make decisions, drawn on the conclusions from the best data of the past, assuming that the future will be similar to the past. Those who doubt this approach are invited to place themselves at the year 1890 (with some instrumentally obtained data of about 85 years long, available at that time), and project the behaviour of those phenomena for the period 1890-1975. How surprised they would be at the accuracy of their projection based on the temporary stationarity of annual precipitation and annual runoff data".

2.1 Streamflow variability - some facts from the past

A general picture of the geographical variation in mean annual runoff throughout the United States is presented in Figure 1. This picture shows there are large geographical variations in the occurrence of streamflow. The amount actually available in any year varies from year to year, and there are even larger variations of daily rates during the year. The nature of streamflow variability varies with size of drainage area as well as with the time interval of interest.

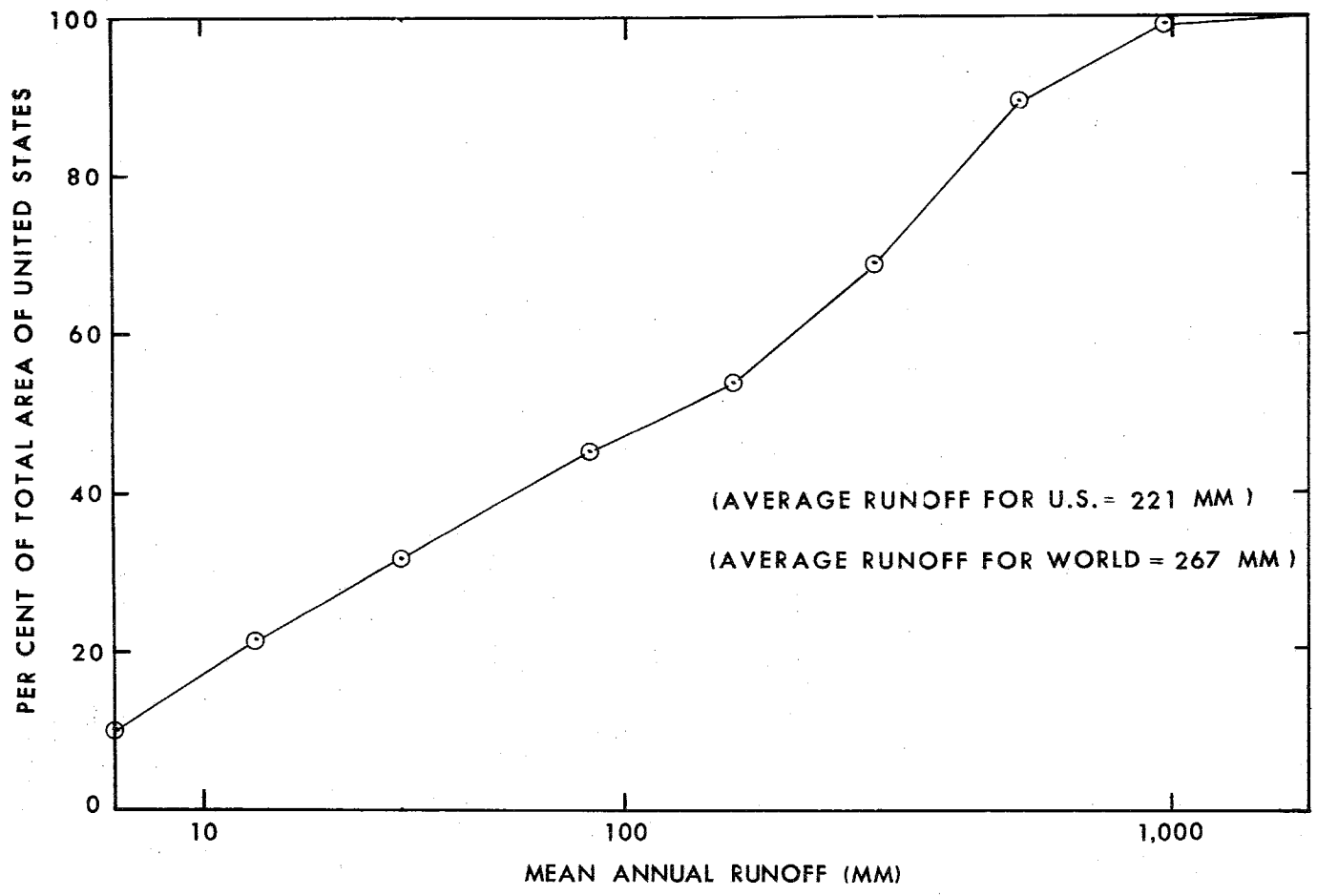


Figure 1. Geographical distribution of mean annual runoff for the United States

One measure of streamflow variability is the ratio of the maximum flow of record to the mean flow. This ratio varies with drainage area. Larger ratios are observed for smaller areas. This is illustrated for the upper Ohio River basin (U.S.A.) in Figure 2. See Linsley, Kohler and Paulus, [4]. This ratio varies also geographically and with basin shape, geology, and climate. High ratios are generally located in arid regions with low normal annual streamflow — which implies the well known fact that societies in arid areas are most vulnerable to climate variability. This is illustrated in Figure 3 for 100 000 square mile drainage basins in the U.S.

Frequency distributions of peak streamflow rates tend to be highly skewed, but average rates of streamflow over periods of a year or two are more nearly normally distributed and less skewed. The appropriate mathematical form for such distributions is still being debated.

Because great variations in streamflow occur over relatively short periods, it is difficult to judge if there are long term underlying trends or cycles involved. Nevertheless, one way to judge if there are long term factors is to consider the time series of annual runoff volumes. From his analysis of large samples of streamflow data on global and continental scales, Yevjevich concluded there was no statistical evidence that cycles exist in river flow time series beyond the astronomical cycle of the year. But there did appear to be some time dependence in series of annual river flow. This time dependence occurs because of the storage from year to year in ground water systems. The distribution of the lag-one annual serial correlation coefficient among 140 basins throughout the world is illustrated in Figure 4. One way to describe mathematically this time dependence is through the use of stochastic hydrologic models.

2.2 Stochastic models in hydrology and their application

During the past two decades hydrologists recognized the need to develop a stronger scientific basis for analysing the effects of climatic variability in the design and operation of water resource systems. Emerging from this recognition has been a new science of stochastic hydrology.

Concern for a scientific basis for diagnosing climate variability in hydrology is not new. Significant contributions to the fundamental theory of probability and statistics can be traced during the last century to many outstanding hydrologists and engineers throughout the world. One manifestation of the development in stochastic hydrology is the growing use of streamflow models to compute synthetic series of streamflow which resemble historical data and which are used as input to simulation models of water resource systems.

Although it is beyond the scope of this paper to consider in detail any of the stochastic models used in hydrology, it is appropriate to examine basic assumptions underlying the development and application of these models. Moreover, applications of stochastic models in hydrology are not limited just to streamflow, but they may apply to the description of other climatic variables such as precipitation and temperature.

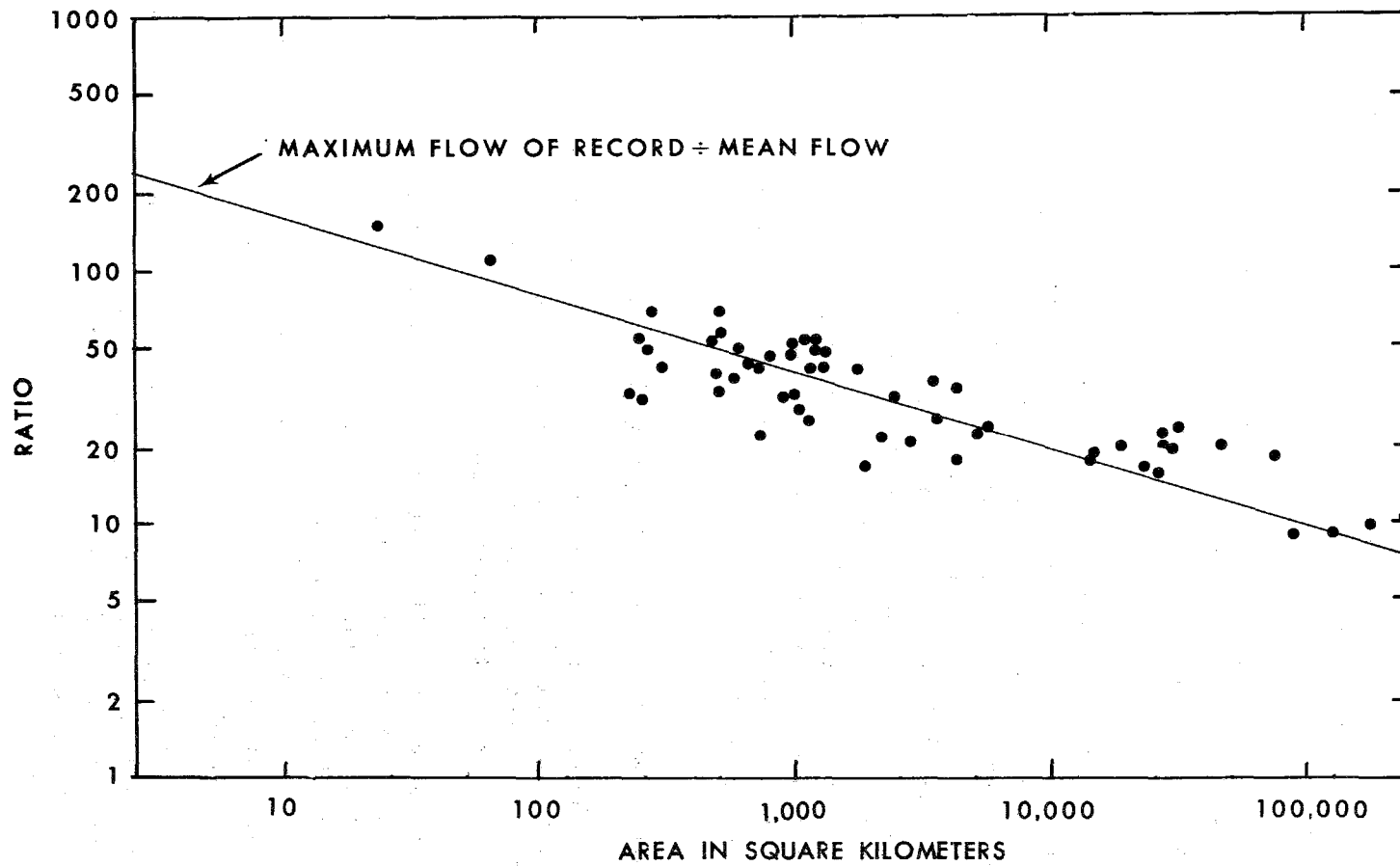


Figure 2. Ratio of maximum flow of record to mean flow for stations in the Upper Ohio River Basin. 4

RATIO OF GREATEST RECORDED PEAK FLOW
TO ANNUAL AVERAGE FLOW
(260,000 SQUARE KILOMETER DRAINAGE IN U.S.)

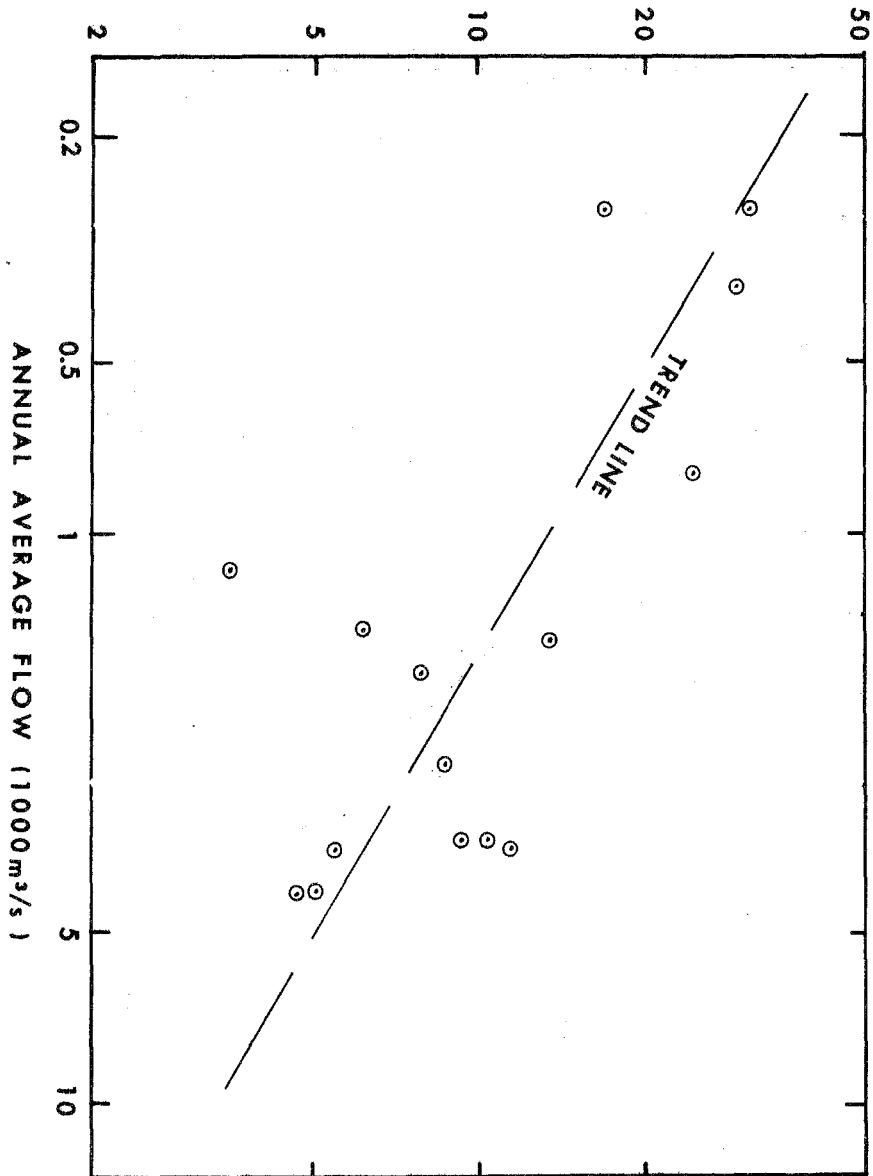


Figure 3. Illustration of tendency for dry climates to have more variable streamflow.

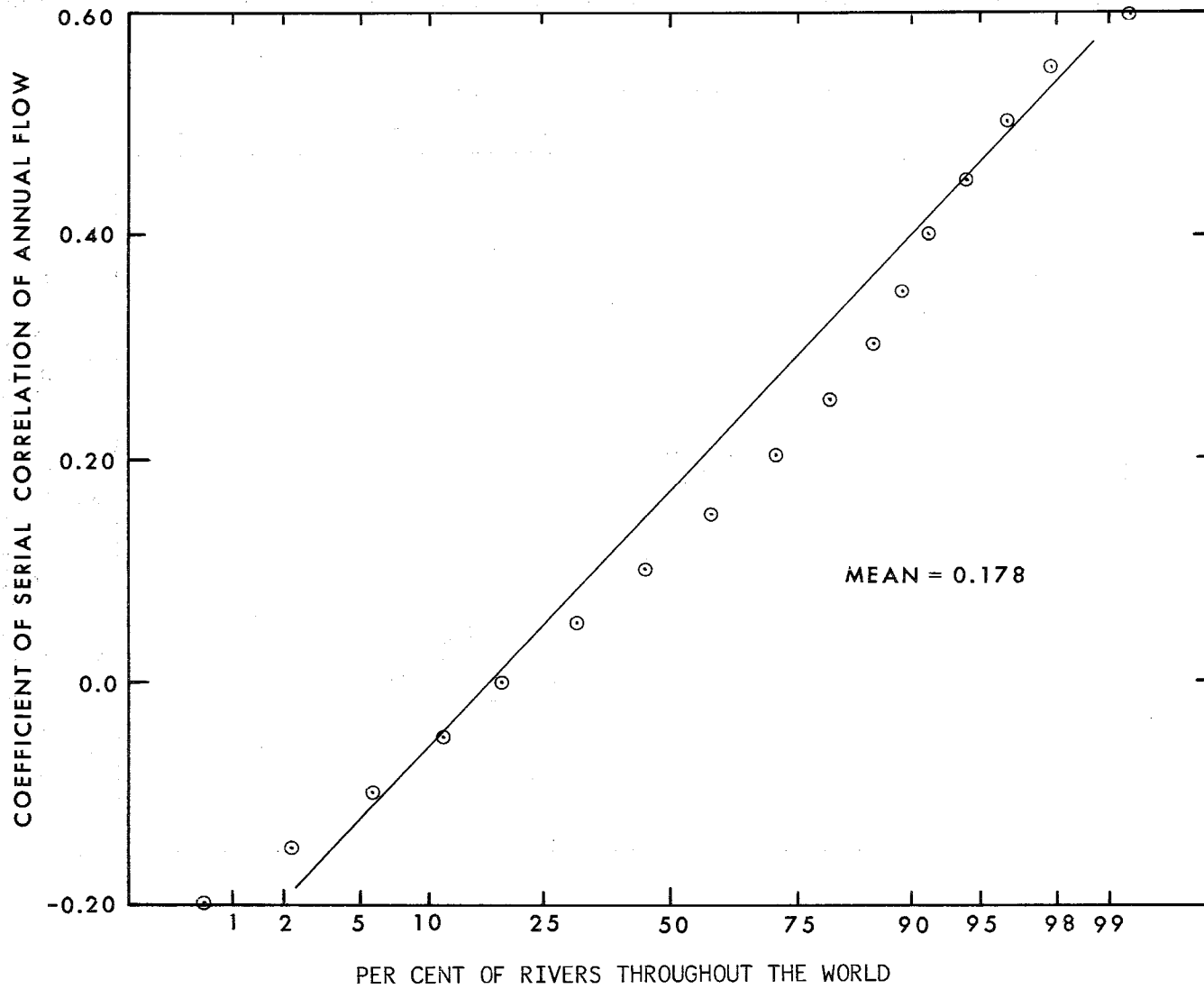


Figure 4. Distribution of serial correlation coefficient of annual flow 2.

Some of the problems inherent in using stochastic process theory in practice are:

- (a) selecting the appropriate mathematical model of streamflow as a stochastic process;
- (b) selecting the appropriate parameters for a given stochastic model on the basis of historical information;
- (c) accounting for the effects of uncertainty in model selection and parameter estimation that arise because available historical information is always limited and never sufficient to remove such uncertainty completely.

One of the primary issues in water resources is to strengthen further the theoretical scope of stochastic hydrology and, more importantly, to find improved practical ways to translate the existing theory into present practice. The major obstacle to more widespread practical use of developed concepts of stochastic hydrology is the lack of adequate mechanisms for transferring the technology into practice. Essential to improved technology transfer is better understanding of the limitations of various stochastic models and of practical implications of the fact that "true" parameter values for any given stochastic model can never be known with 100 per cent certainty.

Stochastic models have been used in hydrology for a variety of purposes, the most common is to generate streamflows - usually for a monthly time interval but also for daily, weekly, seasonal and annual intervals. Such generated series are most often used in simulation models to assess the performance of water resource systems ranging in complexity from a single water supply reservoir to multi-purpose systems involving many interconnected reservoirs. Other practical applications of stochastic models in hydrology include the generation of point rainfall values which are used as input to hydrologic models to translate the rainfall to streamflow. By varying parameters representing human activities such as urban development, farming practices, irrigation, and ground water development, the effects of these activities on streamflow variability may be assessed. Stochastic models of precipitation and temperature can be used in conjunction with deterministic models of physical hydrologic processes to make very thorough assessments of the impact of climatic variations on human activities affected by water.

2.3 Droughts and floods -- how to deal with them

Climate varies throughout the world from very arid to very humid. And climate varies locally with time. Extremes of temporal climate variations often result in floods or droughts.

A very wide range of human adjustments to floods and droughts is possible. Alternative human adjustments to flooding may be grouped into two categories: structural and non-structural. Structural alternatives include construction of flood control reservoirs, levees, and stream channel improvements. Non-structural alternatives include flood plain management, flood proofing of property susceptible

to flood damage, flood warning, and flood insurance. Other structural and non-structural alternatives are also possible.

Alternatives for human adjustment to drought also include structural and non-structural possibilities. The main structural alternative is to construct reservoirs and water transmission facilities to provide water supply for municipal, industrial, agricultural and other uses. There are two principal non-structural alternatives. The first is water conservation, which reduces the amount needed for a given purpose. Conservation practices may be taken in the short run during drought periods, but they may also be taken in the long run to reduce the need for structural adjustments. A second non-structural adjustment is to defer economic development and its greater water demand if structural alternatives are too costly.

Many human adjustments to flood and drought involve some form of action and some process to decide when it is appropriate to take that action. For example, reservoirs used for water supply and hydroelectric power production must be operated according to some type of operating policy. An important problem is to recognize a serious drought situation as early as possible so that appropriate conservation and demand reduction measures may be taken to reduce the risk of emptying the reservoir. Therefore, one of the important needs for climatic information is to establish sound reservoir operating policies that recognize the types of streamflow variations that can be expected in the future.

A key issue is how much information on climatic variability (and streamflow variability in particular) is needed for society to take the best actions in the water resources area. Some insights into approaches for addressing this issue are suggested in the following sections.

2.4 Storage-yield-risk relationship

In the design of water supply systems an important consideration is the risk of failure to meet a given level of water demand. This risk depends on streamflow characteristics, on reservoir storage capacity, and on the required demand and variation of demand during the year. The relationship between storage, demand level and risk is known in hydrology as the storage-yield-risk (or simply storage-yield) relationship.

The storage-yield relationship for a particular reservoir site can be determined if historical streamflow data have been gathered. This involves using historical data to simulate operation of various reservoir capacities to meet various demands, and the risk of failure to meet the given demand in any given year can be estimated from the simulations.

A comparison of storage-yield relationships for a few rivers throughout the world is offered in Figures 5-7. Each figure presents the yield for each river as a function of risk for a given reservoir capacity. Each figure has been scaled so that yield (or demand) is expressed as a proportion of the mean annual flow rate, and storage capacity is expressed as a proportion of mean annual streamflow volume.

Although the storage-yield relationship is an important tool for translating the effect of climatic variability into a required storage to meet a given demand at a given risk level, its practical application is limited to analysis of reservoirs in headwater catchments of complex river systems. When more than one reservoir is involved, the simple concept of the storage-yield relationship does not strictly apply and more complicated water resource systems analysis techniques must be used to assess the effects of climatic variability.

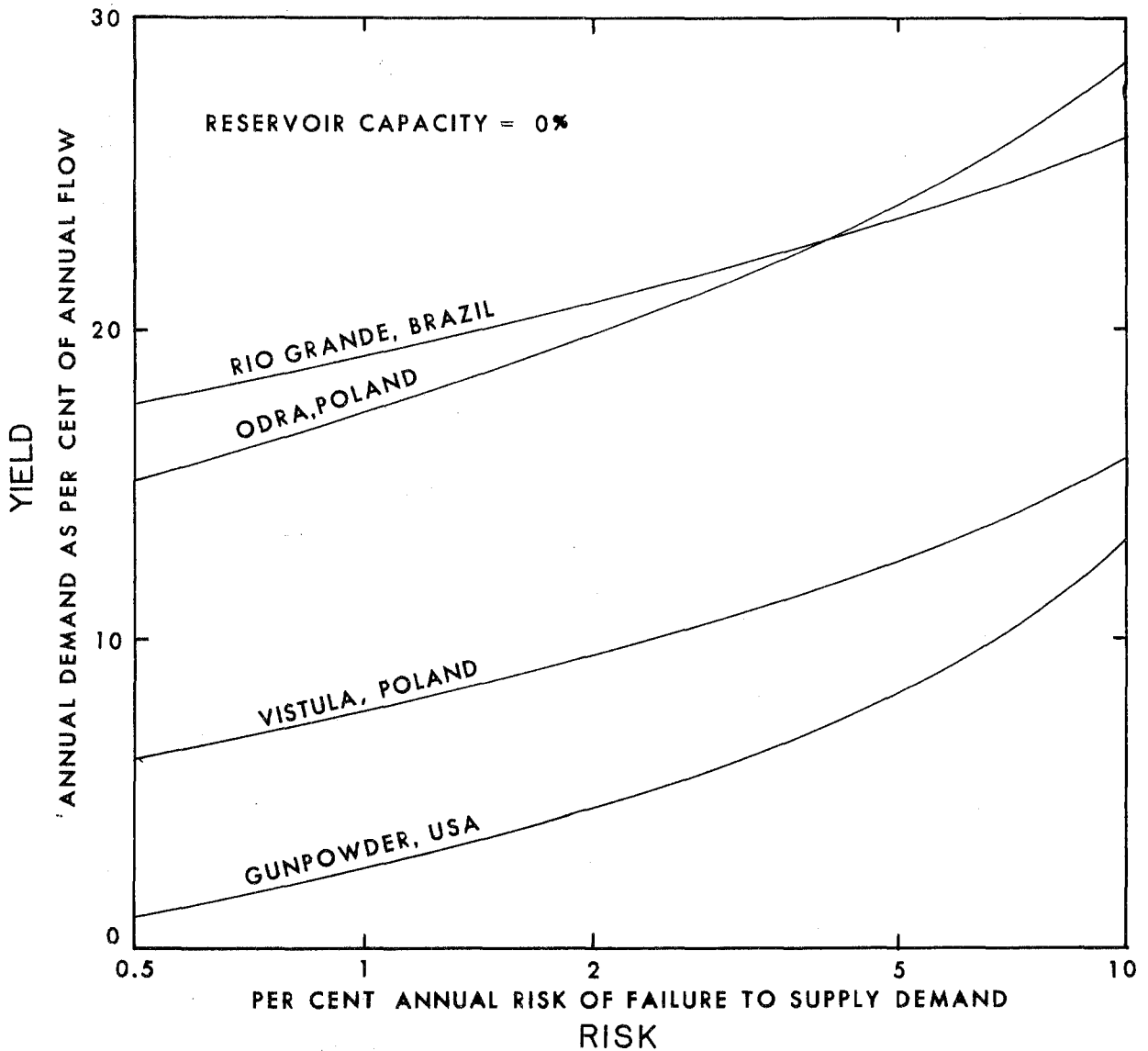


Figure 5. Yield-risk relation with no storage.

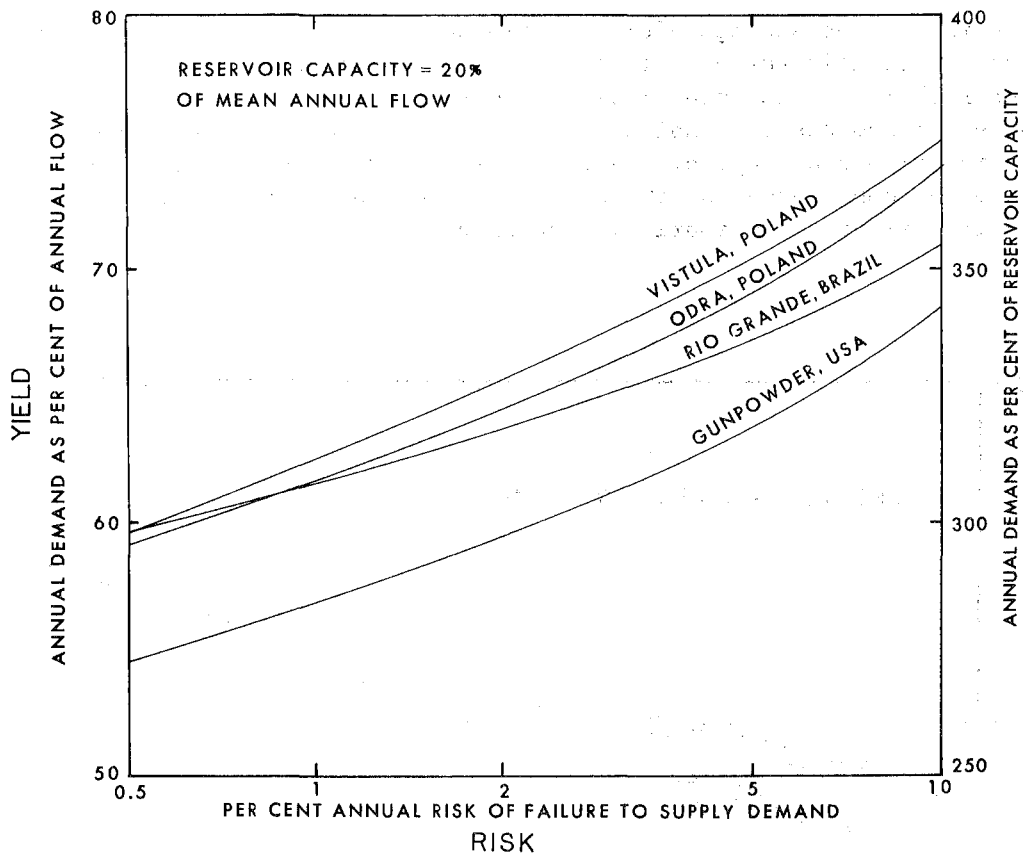


Figure 6. Yield-risk relation for storage = 20 per cent of mean annual flow.

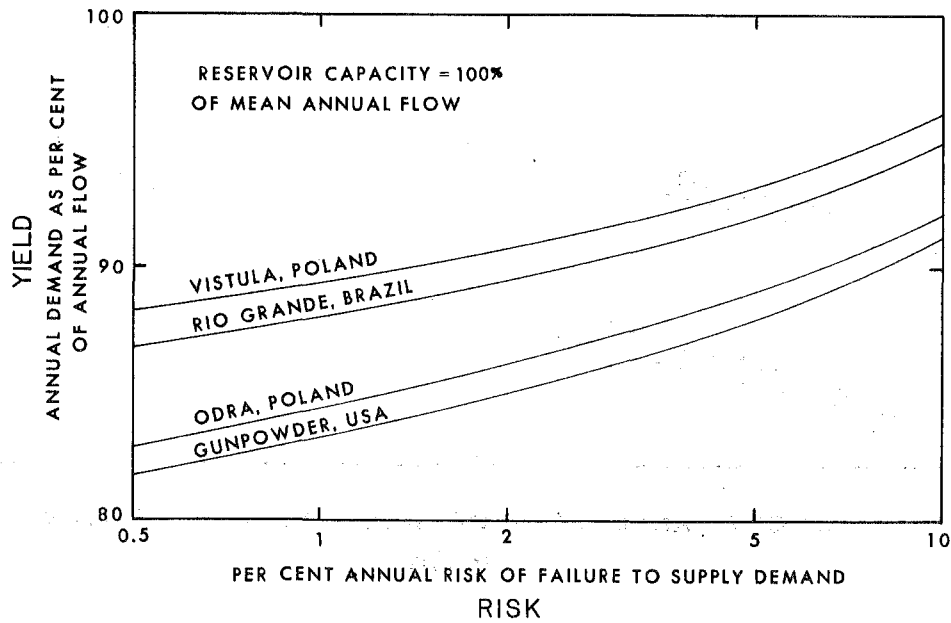


Figure 7. Yield-risk relation for storage = 100 per cent of mean annual flow.

2.4.1 Inferences for collection and analysis of climatic information

Some inferences for the collection and analysis of climatic information may be drawn from the example storage-yield relationship in Figures 5 - 7. If the reservoir is very small (Figure 5), the statistical characteristics of the streamflow govern the safe yield. This situation often occurs when a large river is used for water supply. Enough data are needed to define low flow distributions. Extreme low flows depend as much on the geology of the basin as on the climate. Therefore, mathematical models of the basin hydrology may reduce the length of record needed to make good investment decisions.

If the reservoir is of moderate size (Figure 6), substantial increases in yield can be gained. Annual yields are 3 to 4 times the reservoir capacity and from 3 to 20 times the yield possible at the same risk level without the reservoir. This situation frequently occurs in upland basins in humid regions. The critical streamflow parameter becomes the mean annual flow. Other flow properties are of comparatively minor importance.

If the reservoir is very large (Figure 7), the reliable yield is nearly equal to the reservoir capacity. This situation frequently occurs in arid and semi arid regions. Again, the critical streamflow parameter is the mean annual flow. But, now there is a subtle twist to the nature of the risk. Risk in Figure 7 applies to any future year taken completely at random. In most years, the reservoir will refill at the end of the wet season and the risks will be less than in Figure 7.

But, in some years the reservoir will not fill. The risks, then, become unacceptably high and it becomes necessary to plan and limit the releases from the reservoir to control the risks. This causes occasional water shortages which are not unusual in arid and semi-arid regions.

There is a great need for accurate climatic information during the dry years. Two types of information would be useful. First, historical information on low flow characteristics is needed to judge how much to restrict reservoir releases. Second, probabilistic climatic forecasts for the next several months to a year could improve the risk assessment.

2.4.2 Uncertainty in the storage-yield relationship

Storage-yield relationships are estimated on the basis of historical data. Because the time relationship is unknown, there is some uncertainty in each of Figures 5 - 7. The effect of this uncertainty is to increase the true risks; in other words, the true risks are greater than shown in Figures 5 - 7. The amount of uncertainty decreases as the length of historical record increases.

Uncertainty in storage-yield relationships can be assessed with the aid of stochastic hydrologic models. Although the best procedure to do this is an important matter for future consideration, the idea is to recognize that the historical record is only one series (i.e., a sample) from a large ensemble of series that potentially could have occurred. By chance the others did not occur, but one of these will occur in the future. The problem is to judge how much can be known about the entire ensemble from the available data. This is a problem of statistical inference.

2.5 Importance of water resources variability for regions with different hydrologic and economic conditions - economic, institutional, and legal considerations

As a general rule, climate variability is most important where uses of water are large relative to the supply. This type of situation tends to occur in large metropolitan areas, especially in arid regions but also in humid regions. Arid regions are especially susceptible because not only must municipal and industrial needs be met from limited water supply but irrigation needs must be met as well.

Perhaps the most difficult to understand are the social impacts of water resource variability which occur in developing countries. This is because the social, economic, and political factors vary from one developing country to another, and it becomes essential to consider climatic impacts in the particular socio-economic system in which they occur. Such socio-economic systems often have geographical boundaries that extend beyond the region of the physical climatic variation and may include, for example, the entire system of world food prices as well. In assessing the impact of climatic variability on one segment of society, it is essential to understand how that segment of society interrelates with the rest of society on local, regional, national, and international scales. Because these interrelationships are very different for developing and developed countries, the effects of climatic variability also are very different.

2.5.1 Economic consideration — an example

An interesting example of the economic effect of climatic variability is offered by a hydroelectric power development in Brazil. On the Grande River, Brazil, there is a cascade of power plants. Located at the upstream end of the cascade, at Furnas, there is a large reservoir having a storage capacity of 15 billion cubic metres. The Grande River at Furnas drains approximately 54 thousand square kilometres. The Furnas Reservoir is very important because if the reservoir were emptied according to some simple rule, the water stored would account for 22 770 megawatt months of energy. This is roughly 50 per cent of the total energy produced in the region. Figure 8 shows the storage-yield relationship for Furnas, but there is some uncertainty in this relationship. Two curves are given for the same risk level. One curve was derived from the historical records, the other was derived with the aid of a simple stochastic (Markov) model of streamflow having statistical parameters estimated from the historical streamflow record.

A number of interesting issues are suggested by this figure. First, up to a demand level equal to 60 per cent of the mean annual flow, the two curves agree on the storage requirement to meet the demands. Above a demand equal to 60 per cent of the mean annual flow the two curves diverge, and there appears to be considerable uncertainty in the true storage-yield relationship. For example, if power generation required 80 per cent of the mean flow for the year, the storage required to produce this flow rate according to the stochastic model is equal to 48 per cent of the mean flow. But, according to the historical curve, a reservoir capacity equal to 84 per cent of the mean annual flow would be required. This implies considerable uncertainty in the true reliability of the entire power system in the area. If the simple stochastic model is correct (which is not likely), an extensive construction programme of other reservoirs and power plants could perhaps be delayed.

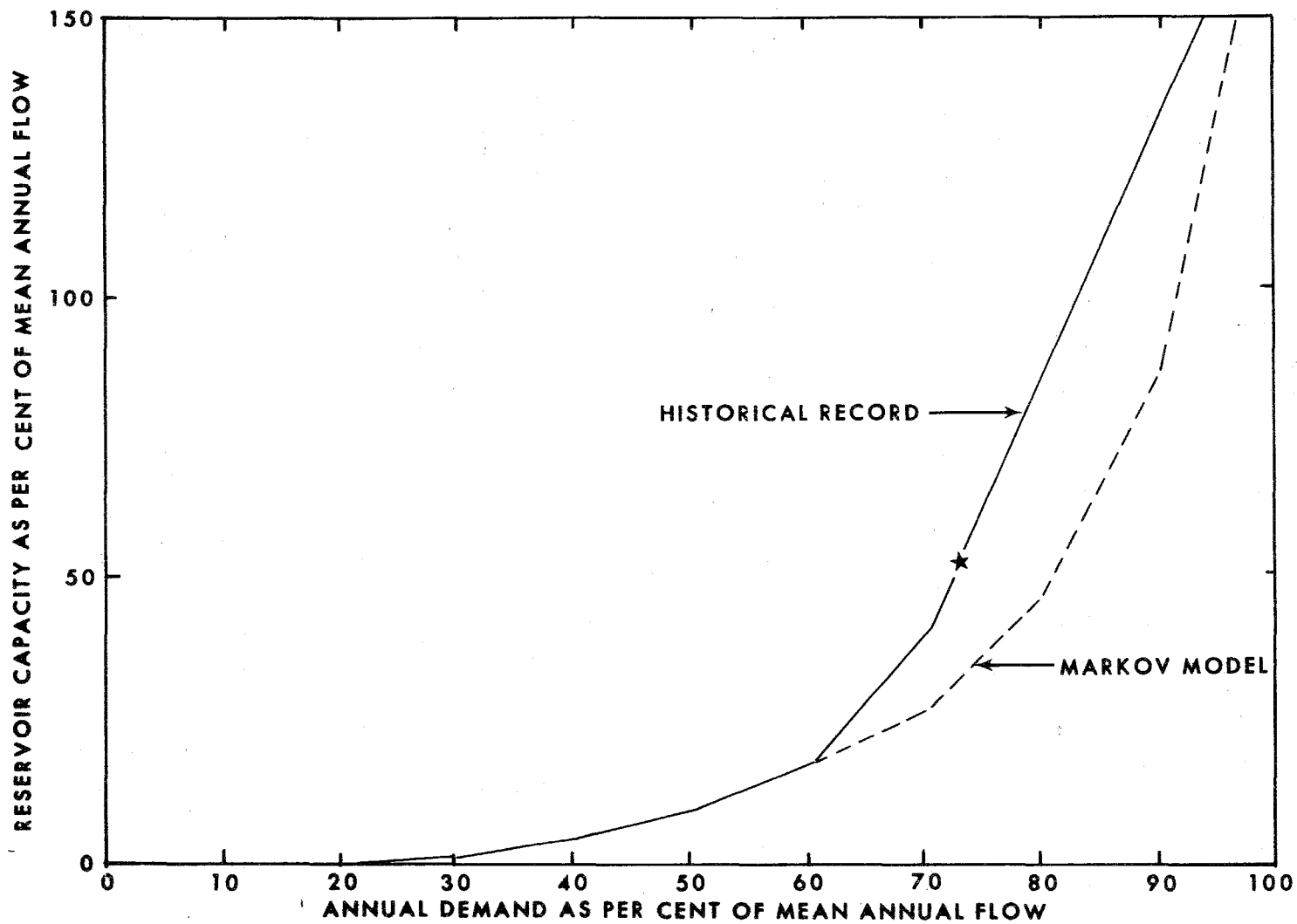


Figure 8. Estimated Storage-Yield relations for Furnas Reservoir.

There are a number of important conclusions for future climate studies to be drawn from the Brazilian hydroelectric power example. If the historical streamflow record at Furnas had been several centuries long, there would be little uncertainty in the true storage-yield relationship. The problem arises because the historical record is only 41 years long, which introduces substantial uncertainty in the storage-yield analysis.

Subjects important for further study in an international programme are:

- (a) what are appropriate roles for stochastic streamflow models in water resources planning, design and operation?
- (b) how does one select the appropriate stochastic streamflow model?
- (c) how should one estimate the parameters of such a model from the limited historical data?
- (d) how can one account for or estimate the uncertainty introduced because of the limited period of historical record of streamflow?
- (e) is it possible to reduce this uncertainty through the use of correlation between the historical streamflow series and other hydrologic related "proxy" series such as tree rings or mud varves?

2.5.2 Legal and institutional considerations

Legal and institutional aspects of climatic variability and its effects on water resources planning and operation are difficult to assess in a general way throughout the world. Nevertheless, a few general statements may be made, because one function of water law is to give stability to institutions and predictability to the results of action. According to Trelease ^[5] the solutions to legal problems created by climatic variability are either engineering or economic. A law that facilitates such solutions must paradoxically combine features of both certainty and flexibility — certainty to encourage investments in projects and flexibility to permit shifts of water between users and uses.

2.5.3 Importance of water resource variability in northeast United States

In considering the possible effects of a climatic change or continuing climatic trend on the water supply system of the northeast United States, Schwarz ^[6] noted there are two major ways in which a climatic change can affect water supply. One is the effect it may have on demand, such as lawn irrigation. The second is the effect on water sources, such as streamflow or ground water recharge. In the northeast United States the second is likely to be far more important in metropolitan water management.

Schwarz noted that the ideal approach to evaluate the effect of climatic change would be to project the trend and magnitude of such change (if known), to translate this into streamflow records, and then to use these records to analyse the response of the present and projected future major water supply systems to the

"forecasted" change. Unfortunately, this straightforward approach is not feasible, except in a limited probabilistic sense, mainly because the magnitude and timing and even the trend of possible climatic changes in specific locations of the world are largely unknown.

Schwarz suggested three feasible possibilities to evaluate the effect of climatic change in the northeast United States. These were:

- (a) to review individual cases and on the basis of their previous response to short-term climatic variations and on the basis of questioning some of the water managers, speculate on the response to climatic and streamflow change;
- (b) to select certain broad criteria of water supply systems and speculate on the effect changes in streamflow statistics might have on each;
- (c) to select a method of synthetic streamflow generation and, using generated streamflow as a substitute for climate, systematically vary the parameters and observe the effects of these variations on the safety of the systems to be developed from this streamflow record.

Schwarz attempted each of these approaches but only the results of the second approach, which are represented in the Table, are concise enough to appear in this paper.

3. Climate and water resources

A basic physical mechanism governing the relationship between climate and water resources is the principle of conservation of water. This means that the rate of inflow in the form of precipitation minus the rate of outflow in the form of evapotranspiration and runoff is equal to the rate of change of storage of water in stream, soil, and ground water systems. If averages are taken over a period of a "water year", beginning and ending during the driest part of the year, the change in catchment storage will be small relative to total precipitation, evapotranspiration, and runoff. In a given year, however, there will be some change in storage of water owing to year-to-year climatic variability. Averaged over many years the expected change in storage becomes negligible. The relationship between average annual precipitation, evaporation, and runoff is referred to as "the annual water balance".

If the effects of climatic characteristics on the water balance are to be understood or classified, some form of transfer function or model relating climate and the water balance is needed. One of the essential principles that must be represented in any transfer function is that runoff is a residual. It is left over after evapotranspiration takes place and after appropriate changes in storage occur as well.

Another dominant factor affecting the water balance is evapotranspiration. Evapotranspiration is the return of water to the atmosphere by evaporation from lakes, soil surface, and through transpiration of water by vegetation. In order for evapotranspiration to occur over the land, water must be available in the soil. In humid regions water is usually available and evapotranspiration rates tend to be close to the maximum possible rate known as "potential evapotranspiration rate".

TABLE
Speculative Impact Matrix of Climatic Change [Schwarz, 1977]

Attributes of Water Supply Systems	Parameters of Climatic Change				
	A Decrease in Mean Streamflow	B Increase in Variance of Streamflow	C Increase in Skew of Streamflow	D Increase in Persistence of Streamflow	E Speed with which Change Occurs
1. Yield from unregulated streams.	Some effects, but likely not to be very large except if change in mean is large or combined with other changes	Severe effects; however, generally short term	Significant effects because number of days of low flow increase relative to few very high flow periods	Significant effects more through duration of low flows than severity	Not applicable
2. Yield from reservoirs	Significant to severe effects particularly if reservoirs develop a high percentage of the average flow	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Medium to no effects depending on size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Significant to severe effects especially if reservoir long-term storage is limited	Not applicable
3. Yield from groundwater	Significant in the long run, especially if draft on aquifer is near average recharge	Little if any significance	Little if any significance	Effects severe and of long duration	Not applicable
4. Quality of raw water	Probably insignificant effects except where large reservoirs are drawn to very low levels	Generally no effects except possible increase in turbidity during high flows	Little if any significance	Little if any significance	Not applicable
5. System reliability	Some effects, other than effects accounted for under 1-4	Some reduction due to constant change in flows in addition to effects under 1-4	Little or none, other than effects under 1-4	Little or none other than effects under 1-4	Sudden changes severely affect reliability, slow ones less or not at all
6. Effectiveness of inter-system and interbasin connexions	No change	Increased effectiveness if variance increases	Little effect	Reduced efficiency of interconnexions because long droughts are usually also widespread	No change
7. Magnitude and control of demand	No significant effect	No significant effect often reoccurring short-term restrictions may reduce their effectiveness	No significant effect	No significant effect; emergency restrictions likely to become less effective over long droughts	Significant and visible effects; relatively fast changes could force major steps toward conservation and demand control
8. Cost of operation of water system	No significant effects except for additional construction that might eventually ensue to alleviate long-term shortages	Possible increase due to turbidity, increased pumping between systems if applicable; possible additional reservoir construction	No significant effects likely	No significant effects except search for new sources	No effects
9. Pressure on and ability of the water system to respond to change	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would be created, but rapid return to normal may for some time inhibit expansion	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would not be affected by hydrologic event	Pressure for expansion would mount over time and increase likelihood of action; however, long high flow periods may inhibit development	Sudden or relatively near future changes could increase action; long-term changes (20 years +) even if known would likely be ignored by existing institutions

The potential evapotranspiration rate is approximately the rate that water would evaporate from a large surface under the prevailing meteorological conditions. Evapotranspiration in humid regions is closely related to temperature as shown in Figure 9, Langbein et al [7].

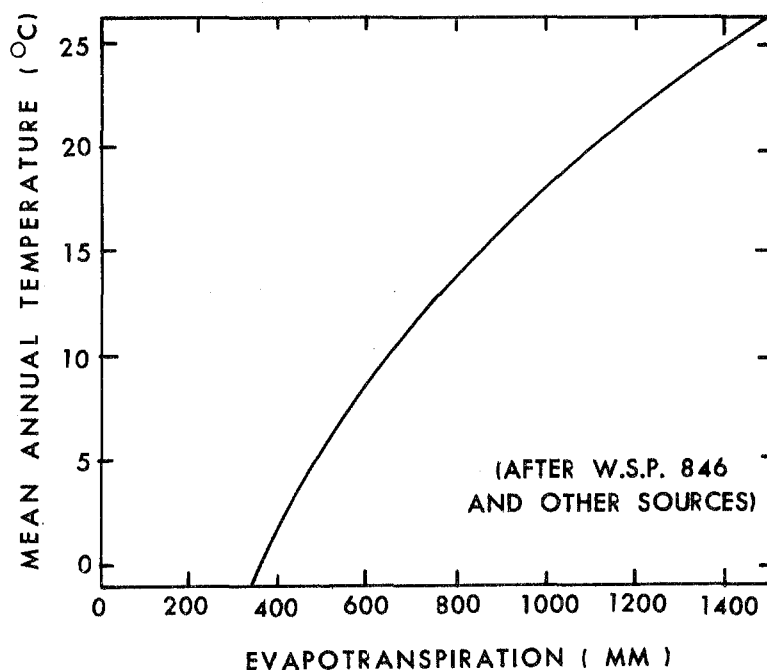


Figure 9. Relationship of annual evapotranspiration loss in humid areas to temperature [7].

The general balance between annual precipitation, runoff, and evapotranspiration (actually, temperature) is illustrated in Figure 10, Langbein et al. [7].

3.1 Climate and water resources variability

Because runoff is a residual, annual variations and geographical variations in precipitation and evapotranspiration tend to be magnified in their effect on streamflow variability. For large geographical areas of a given size, those producing the smallest amounts of runoff per unit area are shown to have the most variable streamflow characteristics. Evidence of this appears in Figure 3. A significant corollary of this for climate studies is that longer historical records of streamflow are needed in arid areas to get the same relative accuracy as in humid areas.

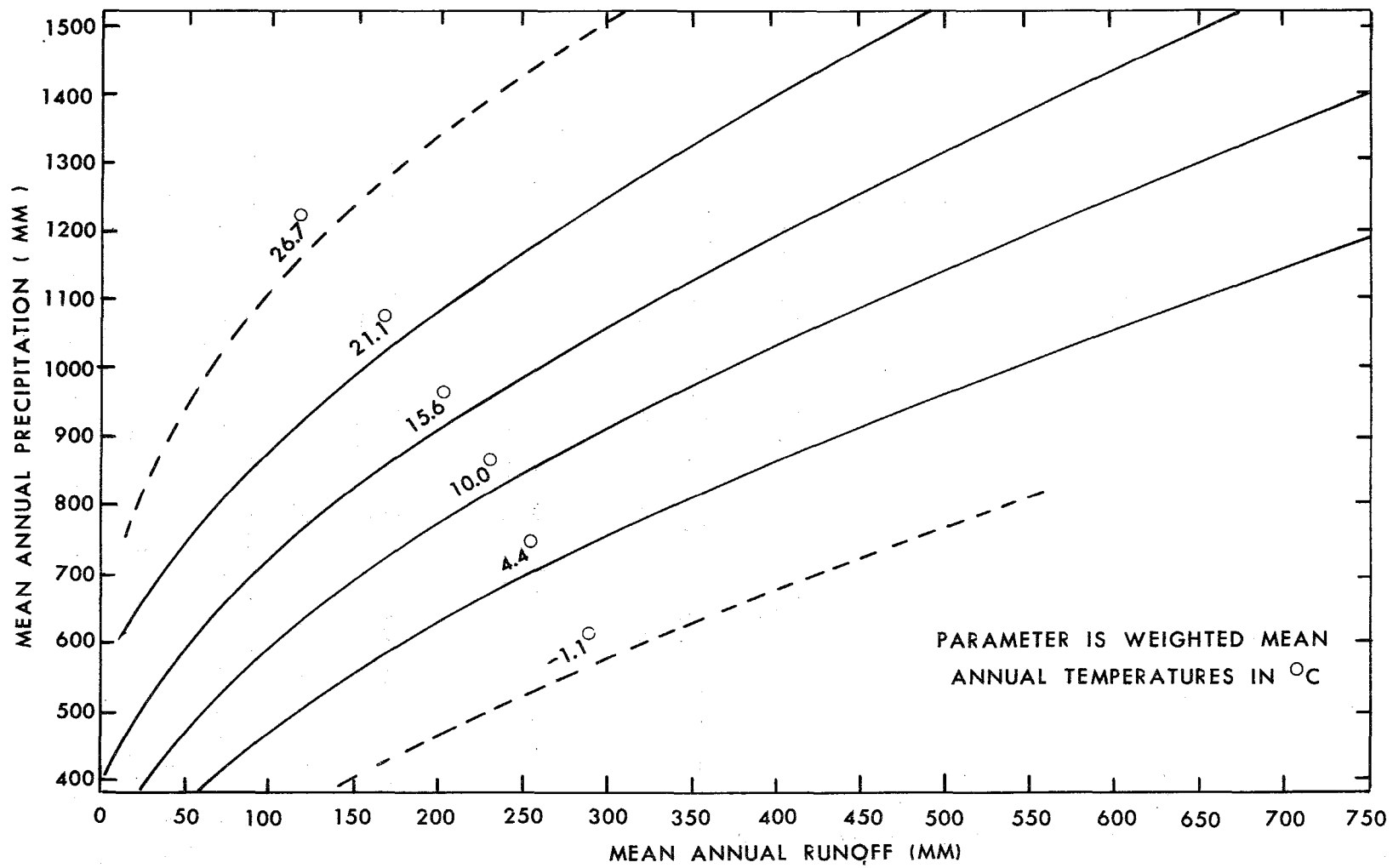


Figure 10. Relationship of annual runoff to precipitation and temperature 7.

3.2 Transfer functions from climate characteristics to water resources values

Transfer functions for relating climate characteristics to water resources values may be classified into three general categories: Statistical, analytical, and numerical. Underlying each must be some degree of physical theory, although the theoretical base tends to become more complete as one moves from the statistical through the analytical to the numerical transfer functions.

Statistical transfer functions tend to be empirical relationships between climate-related variables such as tree ring indices, mud varves, and measures of drought or glacial activity 8.

Analytical transfer functions are based on simplified physical principles that can be expressed mathematically as a system of simultaneous equations. These equations represent the balance between precipitation, evapotranspiration, runoff, and changes of storage in soil moisture, the ground water system, and the stream channel network 9.

Numerical transfer functions may take the form of a conceptual hydrologic model, which allows more detailed physical consideration than in the analytical model. Numerical transfer functions also require digital computers for their application. They typically have parameters that must be estimated from historical data because some parameters may depend on the current climate. Conceptual hydrologic models could be most valuable for assessing the effects of incremental changes in the climate.

3.2.1 Statistical transfer function

Tree ring records and other paleoclimatic indicators are appealing accounts of historical events because they have a wide geographical base, and are continuous, spanning several centuries. Matalas and Fiering 8 note that when a simple statistical model, such as one obtained by regression analysis, is used to reconstruct streamflow data from tree ring indices, certain statistical properties inherent in the tree ring data are passed on to the streamflow data. Unfortunately, not all of the characteristics of streamflow variability can be inferred from the properties of the tree ring indices. Tree ring indices are more normally distributed and more highly autocorrelated than streamflow data. More work is needed to develop and test appropriate statistical transfer models for using paleoclimatic information to obtain improved estimates of streamflow parameters.

3.2.2 Analytical transfer function

Eagleson 9 expressed the instantaneous vertical water and energy budget at a land-atmosphere interface. In terms of physically-based dynamic and conservation equations, these express the rate of infiltration, percolation to ground water and capillary rise from the water table during rain storms and inter-storm periods in terms of independent variables representing the climate (precipitation and potential evapotranspiration), soil properties and water table elevation. Eagleson also introduced uncertainty into these equations through the probability density function of the independent climate variables, allowing the probability distribution to be derived for

the dependent water balance elements: surface runoff, evapotranspiration, and ground water run-off. A long term average water balance is given by the mean values of the independent climatic variables and the dependent water balance elements. This balance, to the first order, defines the annual water balance in terms of physical parameters of the soil climate and water table. Eagleson explored systematically the sensitivity of the annual water balance to changes in the climate and soil parameters. He found that qualitative behavioural changes occurred only with respect to those parameters which change the evapotranspiration and hence vary the basic climatic regime between the arid and humid extremes.

3.2.3 Numerical transfer function (conceptual hydrologic models)

Conceptual hydrologic models that would be appropriate for use as a numerical transfer function for climate studies would represent the physical processes of the hydrologic cycle. These processes might be represented by simple or by more complex mathematical formulations. Models that may eventually prove appropriate for this purpose are already being used routinely by national hydrological services. In fact, such models are being used for short and long term forecasts by the United States National Weather Service.

There are three main technical factors that ultimately limit the application of any climate transfer function, including conceptual hydrologic models. These are the inherent accuracy of the model, the degree to which model parameters depend upon the climatic condition for which the model was calibrated and the accuracy of the available input data to the model.

At the present time there is very little information on the specific nature of each of these three potential error sources. Future climatic studies should attempt to deal explicitly with each of them. Studies that previously have been made of errors in conceptual hydrologic models have been more concerned with representing specific historical events and with minimizing the total combined error induced by all three of these factors. No systematic attempt has been made to sort out the individual error sources. Climatic studies are less concerned with specific individual events than with the distribution of events. They, therefore, are much less sensitive to certain types of errors — provided the range of variability of the climatic variables is large compared to model and measurement errors.

Perhaps the most notable study to understand the error properties of conceptual hydrologic models was conducted by WMO in its inter-comparison of conceptual models used in operational hydrologic forecasting 10. The intercomparison involved the testing of 10 conceptual models on 6 standard data sets and included the subsequent evaluation of the discharges simulated by the models. The resulting differences between simulated and observed discharges represent the compounded effect of the inherent model error and the measurement errors associated with the input precipitation data and the observed streamflow data. No attempt was made in the WMO study to define the accuracy of either the mean areal precipitation estimates derived from the original point precipitation measurements or the accuracy of the discharge measurements. More importantly, no attempt was made to determine the effects of such errors on the differences between simulated and measured discharges.

Therefore, it is not possible to use the results of the model intercomparison testing to estimate the inherent model error as distinct from the simulation errors. This is an important distinction because if a conceptual hydrologic model were to be used to test the effect of incremental changes in a climate variable such as precipitation, only the inherent model error and not precipitation measurement errors would limit the value of the model.

As future climatic studies begin to assess explicitly the individual components of conceptual model errors, a conceptual model of the errors themselves will be needed. A potentially useful theoretical framework for such errors already exists, and is known as Kalman filter theory. Applications of this theory to conceptual hydrologic modelling are needed to assess the ultimate limitations of conceptual models as climatic transfer functions.

4. Potential usefulness of climatic information for water management

Three categories of climatic information are potentially useful for water management:

- (a) historical measurements and statistics of climatic variables such as temperature, precipitation, and potential evapotranspiration;
- (b) paleoclimatic information which might be used through climatic transfer functions to improve estimates of the statistical behaviour of streamflow;
- (c) forecast probabilities of future variation in climatic variables.

Climatic statistics are needed in the design of water resource systems and in the development of water resource system operation plans and policies. Where reservoirs are involved, the most important climatic statistic tends to be the mean annual streamflow. Where reservoirs are not involved, statistics of high and low streamflow extremes are needed. In arid areas the streamflow tends to be more variable than in humid areas, and longer historical records are needed to get statistics of comparable accuracy.

Paleoclimatic information, such as tree rings and mud varves are potentially useful because of the long historical period provided by these proxy data. But improved quantitative methods are needed to assure that climatic transfer functions faithfully produce improved estimates in streamflow statistics than otherwise can be estimated. This will involve modelling of the relationship between the streamflow data and the paleoclimatic indicator. It will also involve modelling the noise or error structure inherent in the transfer function.

Climatic forecasts of precipitation, temperature and evapotranspiration need not be in the form of an accurate deterministic prediction of future events. Water managers have always made decisions under uncertainty and are developing improved technology to do this. Any information on future climatic fluctuations that would tend to reduce uncertainty would be useful. Recognizing this, the U.S. National Weather Service has already begun a programme of forecasting long-range

streamflow in probabilistic terms. This involves simulating for each forecast a number of probable sequences of precipitation, temperature and potential evapotranspiration. If more is known than is implied by the historical record on the possible occurrence of the future sequences, then that information can be used to influence the sequences used in the simulation. Additional climatic studies are needed to consider improved ways of using probabilistic climatic forecasts in extended streamflow prediction.

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CLIMATE, HEALTH AND DISEASE

Wolf H. Weihe*

1. Introduction

In his book on "Airs, waters and places" the forefather of western medicine, Hippocrates in ancient Greece, described the interrelationships among the meteorological, hydrological and topographical properties of the human environment and expressed his belief that human beings are affected by these factors both physiologically and psychologically. Early in the last century the German natural scientist and geographer Alexander von Humboldt incorporated the interrelationship between man and the atmosphere in a definition of climate: "All modifications in the atmosphere which affect our senses markedly, namely, temperature, humidity, changes of the barometric pressure, wind, the amount of electric tension, the purity of the atmosphere or its admixture with more or less noxious gaseous exhalations, finally the degree of habitual transparency and clarity of the sky which is not only important for the organic development of plants and the maturation of fruits, but also for mood and entire well-being of man" 1.

The development of the two disciplines, meteorology and medicine, led them much apart during the latter part of the last century. The common ground became smaller, and there was a time when researchers or practitioners of either science with interdisciplinary interest were looked on as eccentric outsiders.

Since World War II the interest of medical men in climate has risen steadily. Small national groups of interdisciplinary researchers have worked together in international societies such as the International Society of Biometeorology, founded in 1956, or in research projects such as the study of Human Adaptability during the International Biological Programme from 1964 onwards.

The science which investigates "the interrelationships of atmospheric processes and man" is now called human biometeorology. In projecting the many local, chiefly national traditions, schools, movements and fields in human biometeorology against this wide definition one is confronted with a bewildering diversity of interests. It reaches from extensive epidemiological studies on human populations under different climates to the untiring search for mysterious biotropic factors from

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outer space hitherto unknown. Depending on the local climatic conditions interest is more focussed either on weather or on season. In the west European countries where a high weather variation exists nearly all attention is devoted to the effects of weather. Larger scale studies considering weather and climate have been carried out in the United States of America and other industrialized states of the northern and southern hemisphere. Intensive studies on the effect of altitude since the mid-sixties considered population groups in the High Andes 2. Where tropical diseases are still the main concern as in African countries only scattered information on the effects of climate on the population is available.

In view of the diversity of investigations and uneven distribution of information in human biometeorology, it is of great value that the present conference enlarges the scope of investigations of the effects of climate on man to a global scale. This review aims to provide relevant information from various fields of human biometeorology which will serve as a basis for the discussions on the possible effects on man of a major climatic variation in the near future.

1.1 Health and disease

In the constitution of the World Health Organization (WHO), health is defined as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" 3. Well-being is a multifaceted conception to which not only physiological and mental factors but also sociological, economical, political and religious factors contribute. It is understood here as a balance between man's requirements for physical and mental performance and the conditions of his physical environment.

All morbid entities have recently been listed in the International Classification of Diseases, of which the ninth revised edition was published by the World Health Organization in 1977 4. This list is of the greatest value in international studies on climate and diseases, for it provides generally valid reference points.

1.2 Climate

Climate, as Kendrew stated, "is a composite idea, a generalization of the manifold weather conditions from day to day throughout the year. There are regions, especially on the equator, where the weather is so little changeable that weather and climate are almost synonymous. Any one day is a fair sample of the climate. The farther we go from the equator the greater becomes the variation" 5. The same can be said about the higher we go in terrestrial altitudes.

The common method of expressing climate in terms of mean values over reference periods obscures much of the variation of conditions. It is just this variation of conditions that affects man. Hence, he wants to know the variability of mean values for a defined region. There are two characteristic kinds of variability to which man has to adjust:

- circaperiodic changes, occurring with regular frequency and amplitude, such as day-to-night, or summer-to-winter;

- non-periodic or aperiodic changes, occurring during a single day or successive days, months or years within a reference period.

There are different ways to express the characteristic variability of the climate of an area, for example, by providing standard deviations from the means, and ranges of maximum and minimum values and frequency distributions for significant variables such as temperature or humidity.

2. Basic principles

Man and the environment around him are two closely linked systems, of which the system "man" has to adjust to the given conditions in the atmospheric system. It may be said that the first system has an aim while the latter has none, it is just there. The aim of the human system is to live and to survive. During his long evolution man has reached his present stage of development through mutation and selection, by trial and error. In this development man is the most successful species of all, for he has managed to advance into every climatic zone between the equator and the poles and to settle down in most of them permanently. In this respect man is challenged by only one other vertebrate species, the rat.

The adjustment of the human system to the atmospheric system is so close that it follows exactly its circaperiodic changes. The regular changes within the body are known as biological rhythms, of which the circadian and circaannual rhythms are synchronized with the climate. The environmental factors act as synchronizers of the endogenous clock.

As there is no standard climate, there can be no standard man. Man is adapted to regional climatic conditions, as expressed by the great variety of types of man. Many characteristics of these types of man are somehow related to the features of the climate where they have lived for many generations. The short fat Eskimo fitted for life in the Arctic is different in appearance from the African Pygmy living in the equatorial forest or his near neighbour, the long-legged Masai, living in the Savannah.

The synchronization of the human body with the periodic changes in the atmospheric environment, and its ability to cope with aperiodic changes therein, is achieved by a concerted regulation of all bodily functions. This consistently operating regulation is known as "homeostasis". It operates for the maintenance of a very narrow variation of conditions within the body in spite of a very wide variation of conditions in the atmospheric environment. The regulation consists in a maintenance of the optimum set of values within the body that guarantee its full function. Homeostasis involves all levels of organization within the body from intracellular molecules on the one hand to organ systems and their integration via the central nervous system on the other.

The phenomenon of homeostasis provides the body with a buffer system, which is called adaptability. Failure, damage or short circuit of any link within the regulation system will necessarily lead to a reduction of the adaptability. Indeed, the limits of adaptability are maximally wide in the healthy person and become narrow in man when his functions fail or he falls ill.

2.1 The heat exchange between the body and its environment

The regulation of the body is maintained through metabolism which is geared to an optimum body temperature of 37 deg C. Consequently, metabolism requires a regular provision of energy from outside in the form of food and the elimination of waste energy.

As the maintenance of the optimum body temperature is of such vital importance, temperature regulation (homeothermia) has been designated as the chief function of homeostasis.

The principle of homeothermia consists in the maintenance of a balance between the heat stored in the body and ambient heat. The net rate at which a body generates and exchanges heat with its environment is mathematically expressed in the heat balance equation:

$$S = M \pm E - (+W) \pm R \pm C \pm K$$

in which

S = storage of body heat

M = metabolic heat production

E = evaporative heat transfer

W = work

R = radiant heat exchange

C = convective heat transfer

K = conductive heat transfer

All positive transfers mean heat gain, and negative transfers mean heat loss. Only M and W are always positive.

The four channels of heat exchange: evaporation, radiation, convection and conduction, are the foundation for the close physical interrelationship of man with his atmospheric environment.

The process of homeothermia is achieved by thermoregulation. Thermoregulation involves sensors for heat in the form of cold and heat receptors which are placed densely in the skin, the inner surfaces and other parts of the body. Messages from the receptors are integrated in the brain stem near the hypothalamus, and from there impulses are emitted via neural tracts to the effector organs. This is demonstrated in Figure 1. Stimulation of the warm receptors will cause activation of the effector organs increasing heat loss, e.g., sweating, acceleration of breathing rate (panting), and dilation of the peripheral vascular beds with warming up of the outer body surfaces.

Simultaneously heat producing or conserving mechanisms will be inhibited. With stimulation of the cold receptors the response will be the opposite [6].

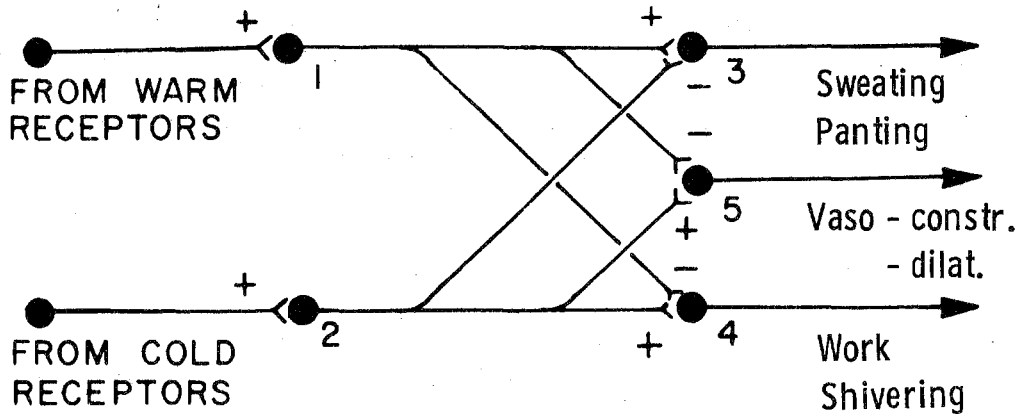


Figure 1. Neuronal model of temperature regulation in a homeotherm. Impulses from warm receptors (1) in the periphery are transmitted to the central integrator in the brain stem. From there activating impulses are transmitted to the periphery to increase heat loss (3), i.e., panting and sweating and vasodilatation (5), i.e., releasing vasoconstriction while heat production is blocked (4), i.e., work and shivering. Impulses from the cold receptors (2) have the opposite effect (Source: [6].)

One very important mechanism by which man controls his thermal balance is behaviour. It must be understood in its widest sense, including body posture, activity, use of insulation materials such as clothes, arranging protection in the form of dwellings, and applying heating or cooling. This vast field of unconscious adjustment and conscious response, which may require man's highest intellectual capacities, can be collectively described as "behavioural thermoregulation".

2.2 Comfort and limits of tolerance

According to the heat balance equation there must be an ambient thermal condition at which a minimum of regulation is required for the body to maintain the optimum heat storage. This thermal condition is known as the "comfort zone". The zone is limited by the lower and upper critical temperatures. Further down the thermal scale at lower temperatures the body will either have to produce more heat or reduce heat loss by means of more insulation. Above the upper critical temperature, the body must reduce heat production through resting, reduce its insulation layers, or facilitate heat dissipation by sweating. Sweating is a very efficient mechanism for heat dissipation and is better developed in man than in any other species. While sophisticated insulation measures nowadays allow a man to move about in temperatures as low as -60 deg C, his life in the heat is more limited, as he has to rely on his sweating capacity for cooling. Moderate deviations from the comfort zone can be tolerated with ease.

The further away he gets from the comfort zone, the more strain is put on man's thermoregulation capacity. The stress can be so great that it can be tolerated only for a limited time. Time as a factor becomes the more important the more extreme the cold and heat conditions are to which man is exposed. The role of duration of exposure to extreme conditions of cold and heat is summarized in the chart prepared by NASA (Figure 2), which shows the time required for limits of tolerance to be exceeded, after which some damage begins to occur. The values are based on empirical estimates and apply to healthy persons with high adaptability [7].

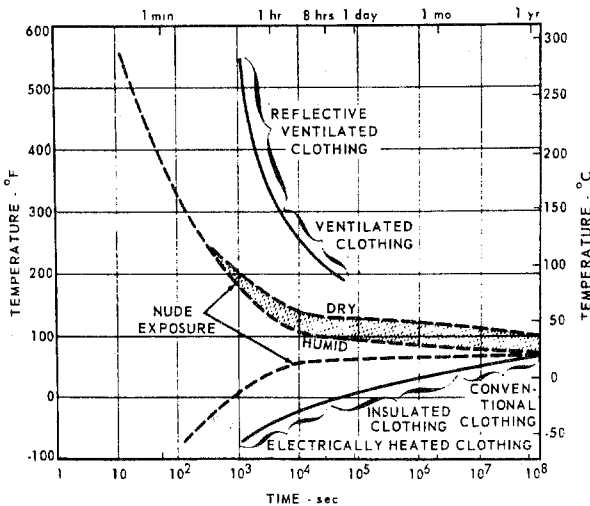


Figure 2.

Tolerance limits of nude and clothed men on exposure to low and high temperatures (Source: [7]).

The limits of thermal tolerance of man can be defined for different purposes. There are the widest possible limits of tolerance for conditions at which individual man can live and work only short periods of days or hours, and there are the narrower limits of tolerance within which individual man can live and work during his entire or certain periods of his lifetime. The most important limits of tolerance are those within which populations can live and reproduce for generations. All climates of the world where permanent human settlements exist fall within this category. The upper T_{max} limits are 55 deg C, the lower T_{min} limits -60 deg C.

In general man's distribution over the Earth is further restricted to climatic zones with vegetation periods of at least 3 to 4 months (Figure 3) if he is to supply his own food.

2.3 Biotropic factors of the climate

The principal biotropic (biologically influential) factor of climate is temperature. Other factors mainly have relative importance with respect to it. Water vapour pressure gains rising influence above 25 deg C while it can be ignored below 10 deg C. Precipitation and rainfall can be biotropic factors through cooling the air and saturating it with humidity. Relative humidity is of importance at all temperatures. Wind acts chiefly through enforced convection with a positive effect

in the heat and a negative effect in the cold. Solar short-wave and terrestrial long-wave radiation can be powerful biotropic factors when they occur with a clear sky. Another major factor is light, which depends on its length of photoperiod and intensity. Ultraviolet radiation is of very specific biotropic action. Barometric pressure becomes important with major changes of altitude, basically because of the change of partial pressure of oxygen.

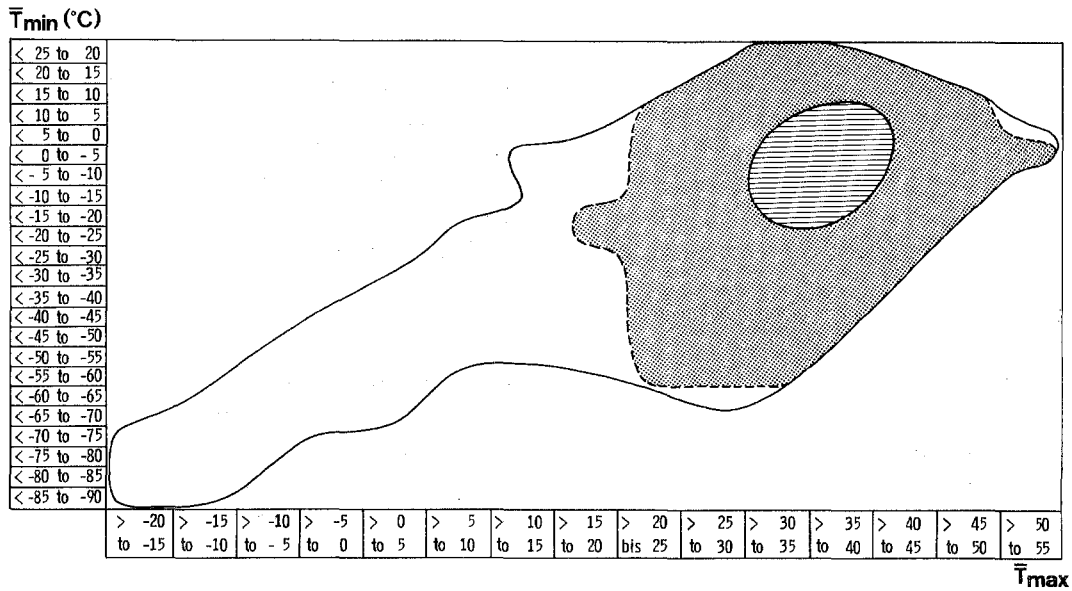


Figure 3. Distribution of the world population in the annual \bar{T}_{min} and \bar{T}_{max} diagram. White area: total terrestrial surfaces. Dotted area: extension of permanent communities of man. Hatched area: zone where over 60 per cent of world population live (Source: 98).

Other meteorological factors not commonly measured such as electromagnetic fields, electric discharges in the troposphere (the sferics), and air ionization have minor biotropic action. They rank in importance far behind the climatic factors that affect the thermal conditions and the thermal balance of man.

Many attempts have been made to combine two or more meteorological factors as indices which were defined according to physiological effects. Air temperature and humidity were linked in the temperature-humidity index by Thom 8. A widely used thermal index is the effective temperature scale by Houghton and Yagloglou taking temperature and humidity of the air and its rate of movement into consideration 9. Radiation as a fourth factor was introduced by Vernon by replacing air temperature by globe temperature 10. Both, the effective temperature and the corrected effective temperature index are based on subjective impressions of warmth and allow a majority estimate of comfort conditions. Other indices deal with conditions of heat such as the Belding-Hatch heat stress index 11, and the Predicted 4-Hour Sweat Rate 12, or of cold such as the windchill and frostbite indices 13.

Some of these indices have been used to classify the surfaces of the continents with respect to human comfort. Gregorczyk and Cena [14] described the distribution of effective temperature, and Gregorczyk [15] used air enthalpy to classify bioclimates for man. Terjung computed the world patterns of the distribution of the monthly comfort index (temperature and humidity) [16], and selected physioclimatic indices for the hot climates of Africa [17]. The wet-bulb temperature and discomfort index were used by Jauregui and Soto [18] to define favourable and unfavourable areas for human settlement in Mexico.

While these comfort indices are primarily worked out under indoor conditions they will have to be corrected for the wider variation of outdoor climate conditions if interest in a definition of bioclimates for man should increase. A promising approach in this direction was made by Fanger [19] with the Predicted Mean Comfort Vote (PMV), which includes relative air velocities up to 1.5 m/s, body insulation from naked to 1.5 clo*(unit of clothing) and various activity levels from 50 to 150 kcal/m².h.

2.4 Adaptability: genetic and acquired adaptation

Adaptability in its widest sense comprises all the ways in which man is fitted to the totality of his environment. Commonly it means the capacity of man to respond to changes in the environment in ways which reduce stress and facilitate survival. Man is seen at the levels of the individual and the population. The process of adaptation is composed of two major components: genetic and acquired adaptation.

2.4.1 Genetic adaptation

In genetic adaptation the environment acts as selecting agent. The selecting process operates in two ways: maintaining genetic stability and producing genetic change. There are selecting forces which act universally and others which act in a particular environment. The adaptability itself has a genetic basis and its capacity is the result of a long selection process. For all the innumerable traits and components of the body a variability is inherited within which they develop and change during the lifetime in interaction with the environment. The variability of some of these traits is wide, such as physiological and behavioural traits, and for some extremely limited, such as structural traits. The totality of all the component variabilities provides the integrated capacity to deal with the various environments and changes in them.

The selecting process on a global scale may be seen in the dense dark pigmentation of man at low latitudes and the progressive decrease at high latitudes. Selective forces in a particular environment have given rise to racial and ethnic differences. The principal question is whether the totality of the genetically determined adaptive capacity differs between these differently defined populations and whether such measurable differences as there are could be decisive in fitness for survival in climatic crisis situations. According to the present state of knowledge these differences in races and ethnic groups are not striking; on the contrary, all

* 1 clo = 0.18 deg C.m².h/Kcal = 0.155 deg C.m²/W.

investigations have shown that the adaptive capacities of sample populations from all parts of the world are extremely large and that there are many ways of compensation in cases of deficiencies.

2.4.2 Acquired adaptation

The physical and mental state to which individuals or populations develop in interaction with their environment is summarized as "acquired adaptation". It can be grossly divided into irreversible adaptation, which is limited to the period of growth and development, and reversible adaptation which occurs at all periods of a lifetime.

An example of irreversible adaptation is the typical barrel-shaped thorax of high altitude populations, which develops in children from low elevation when growing up at high altitudes and does not develop in high-altitude-born children who grow up at low elevations [20]. Irreversible adaptations will be at a disadvantage when the individual leaves the climatic condition in which it has developed to full growth. Reversible adaptation takes place slowly with change of climatic conditions from season to season and rapidly as with temporary adjustments to short-term climatic changes. Cold acclimatization provides higher tolerance to low mean temperatures in winter and heat acclimatization higher tolerance to high mean temperatures in summer. Consequently comfort temperatures will be either lower or higher.

Investigations on communities and groups of subjects during different times of the year and with travel to other climates show that these adaptations are highly efficient and are well within or exceed mean variations between ethnic communities at ages when adaptive capacities are high. For example, data on maximum oxygen consumption of different ethnic groups show no particular differences between Bantu negroes, Kalihar bushmen, Arctic Indians, and Norwegian students (Table 1) [21].

Table 1

Maximum oxygen uptake (ml/min . kg) of men from different ethnic groups, age 20 - 40 years (mean \pm SE) (Source: [21]).

Subjects	n	Max O ₂ (ml/min . kg)
Bantu negroes	23	48 \pm 1.96
Kalihar bushmen	3	47 \pm 6.98
Eskimoes	8	44 \pm 1.81
Arctic Indians	8	49 \pm 1.71
Nomadic Lapps	16	54 \pm 1.27
Alucaluf Indians	4	38 \pm 0
Norwegian students	12	44 \pm 1.10
Norwegian athletes	14	71 \pm 1.80

Reversible physiological adaptation is supported by cultural adaptation. The influences are far reaching of education, training, learning, stimulation, motivation and other components of the cultural pattern of a community to activate and make wider use of the adaptive capacities. It is impossible to estimate the relative importance of these components in the totality of acquired adaptation to improve fitness and well-being in a particular climate.

2.4.3 Dependence of adaptability on age

The adaptive capacity is clearly age dependent. Starting at a very low level in infants, it rises through childhood and adolescence to a maximum which extends up to the age of 30 years. Already during the third decade of life the state of some components of the body begin to decline. A general reduction of adaptive capacity sets in during the fourth decade, which progresses slowly through middle-age and accelerates as old age advances. Man is subject to aging processes which can be seen in the steady diminution of morphological and physiological components, the totality of which is expressed in a decline of his adaptive capacities. This means that his susceptibility to environmental stresses increases and his reserves for homeostasis shrink with advancing age [22].

This age-dependent change in adaptability has been demonstrated in investigations of a host of parameters. Maximum oxygen uptake (a parameter to estimate working capacity) of individuals older than 70 years is only about half of those of 20 or 30 years (Table 2) [21]. To mention another example [23] sweating capacity was found to be significantly reduced in elderly men and women at the periphery as well as on the trunk.

Table 2

Mean maximum oxygen uptake (l/min) of young and old men (Source: [21]).

Age (y)	1938 Boston	1960 Stockholm	1963 Cologne	1964 Oslo
20-29	3.56	-	-	3.20
30-39	3.42	3.01	2.97	3.20
40-49	2.92	2.99	2.68	2.90
50-59	2.63	2.99	2.68	2.90
60-69	2.35	2.23	1.79	-
70-79	1.71	1.99	1.52	1.95
80 and over	-	1.50	-	1.63

The decline of adaptive capacity is delayed in physically well trained individuals, and the continuation of training can further postpone it, while it is accelerated in poorly trained, inactive individuals.

2.5 Model of human population - climate interaction

A simple model (Figure 4) of the interaction between human population and climate can be worked out by combining:

- (a) the periodic changes as a characteristic of climate;
- (b) the population density gradient from moderate towards intolerable climates (Figure 3);
- (c) the comfort requirements of man;
- (d) the adaptive capacity of populations.

Based on the gross density distribution of populations in the $\bar{T}_{\min}/\bar{T}_{\max}$ diagram (Figure 3) the range within which over two thirds of the world population lives is in the \bar{T}_{\min} band from -5 deg C to -15 deg C and in the \bar{T}_{\max} band from 30 deg C to 38 deg C. This zone is taken as the mean comfort range within which adaptation of populations is easiest. The process of adaptation in the broadest sense combines physiological, mental, cultural and technological adaptations to make permanent settlement of populations in a particular climate possible and comfortable. An optimum annual mean temperature is marked in the middle of the mean comfort range. The limits of tolerance for populations are at 55 deg C \bar{T}_{\max} and -60 deg C \bar{T}_{\min} .

Within the absolute limits of tolerance three zones can be classified according to the extent of adaptation required:

- moderate; this zone is identical with the comfort range;
- intermediate;
- maximum; in this zone without the highest adaptive capacity life will be intolerable.

The zones are labelled on the right of Figure 4. For each zone there is an upper part in the heat range and a lower part in the cold range within which the climatic hazards increase outwards.

The model will be used in a later section to demonstrate the consequences that a major global climatic variation would have on world populations.

3. Climate and health of man

3.1 Nutrition

The FAO/WHO Committee on Energy and Protein Requirements 24 has defined energy requirement as "the energy intake that is considered adequate to meet the energy needs of the average healthy person in a specified age/sex category. Some individuals need less and others more than the average energy requirement, but in a group these surpluses and deficits cancel each other, and the suggested requirement represents the average of the group".

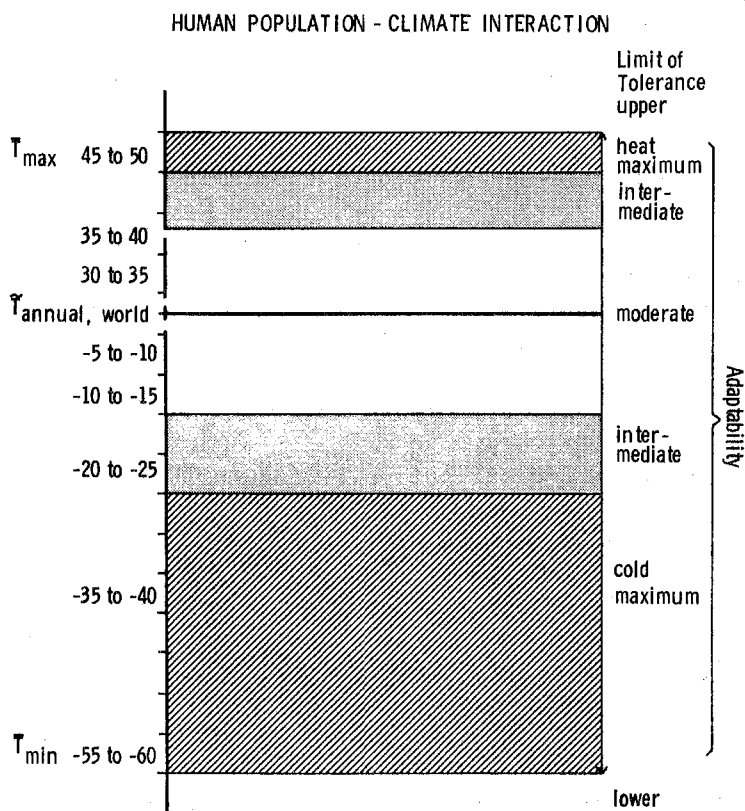


Figure 4. Model of population-climate interaction based on data of Figure 3. White zone: range of \bar{T}_{min} and \bar{T}_{max} bands where over 60 per cent of world population live, requiring moderate adaptability. Grey zone: range where about 30 per cent of world population live, requiring intermediate adaptability. Hatched zone: range where less than 10 per cent of world population live, requiring maximum adaptability near the limits of tolerance.

The requirements depend on:

- (a) physical activity;
- (b) body size and composition;
- (c) age;
- (d) climate; and
- (e) living conditions.

The minimum energy necessary for the maintenance of the body is used up for the basal metabolic rate (BMR), which is the heat production under resting and fasting condi-

tions. An additional amount of heat above the BMR derives from the absorption of food and minimum levels of muscular activity required for eating, dressing, etc. It is estimated that the energy cost of maintenance is 1.5 x BMR.

The basal metabolic rate does not change much from the standard estimates, and there is no evidence that energy requirements differ between ethnic groups as long as size, weight and activity are the same.

The effects of body weight and physical activity on energy requirements of men are given in Table 3 24. The corresponding estimates of energy requirements for women are about 15 per cent lower at light activity and 13 per cent lower at exceptionally high activity.

Table 3

Energy requirements of men according to body weight and physical activity (From 24).

Body weight (kg)	Light activity		Moderately active		Very active		Exceptionally active	
	(kcal)	(MJ)	(kcal)	(MJ)	(kcal)	(MJ)	(kcal)	(MJ)
50	2 100	8.8	2 300	9.6	2 700	11.3	3 100	13.0
55	2 310	9.7	2 530	10.6	2 970	12.4	3 410	14.3
60	2 520	10.5	2 760	11.5	3 240	13.6	3 720	15.6
65	2 700	11.3	2 000	12.5	3 500	14.6	4 000	16.7
70	2 940	12.3	3 220	13.5	3 780	15.8	4 340	18.2
75	3 150	13.2	3 450	14.4	4 050	16.9	4 650	19.5
80	3 360	14.1	3 680	15.4	4 320	18.1	4 960	20.8

The effects of age on energy requirements of moderately active adults are summarized in Table 4 24. The values are stable in the age group from 30 to 39 years at the highest level. With increasing age the energy requirements decrease during the two decades from 40 to 59 years less than during the later decades from 60 to 79 years of age. The decline of energy requirements with age reflects the above described process of slowing down of all physiological functions with advancing age.

The effect of climate on a healthy individual man should be reflected in a high energy requirement in a cold climate and a low one in a hot climate. The First and Second FAO/WHO Committee 25 defined a "reference man and woman" as living in a climatic zone at a mean annual temperature of 10 deg C (Table 5) 25. It was decided by the Second Committee that the energy requirement would increase by 3 per cent for every 10 deg C below the reference temperature and decrease by 5 per cent for every 10 deg C above the reference temperature. This rule is, however, no longer applicable with the improvement of the socio-economic conditions in most countries.

Table 4

Energy requirements of moderately active adults according to age (Source: 25).

Age (years)	65-kg man		55-kg woman		per cent of reference
	(kcal)	(MJ)	(kcal)	(MJ)	
20-39	3 000	12.5	2 200	9.2	100
40-49	2 850	11.9	2 090	8.7	95
50-59	2 700	11.3	1 980	8.3	90
60-69	2 400	10.0	1 760	7.4	80
70-79	2 100	8.8	1 540	6.4	70

Table 5

Estimated energy requirements of young reference adults for 3 weight groups at various temperatures (Source: 25, 49).

Mean Annual Temperature deg C	kcal per day					
	50 kg		65 kg		70 kg	
	Men	Women	Men	Women	Men	Women
0		2 479		2 472		2 442
5		2 444		2 436		2 407
10		2 408		2 401		2 372
15		2 349		2 341		2 313
20		2 290		2 282		2 254
25		2 230		2 222		2 195

There is insufficient information on the activity patterns of normal adapted populations in hot climates. Man, with the exception of very poor small population groups, has changed his way of life so much during the recent decades that he is less effected by low temperatures below the lower critical comfort temperature. He has improved his protection against both increased heat loss and high impact of heat. This permits him to maintain a microclimate around his body surfaces near 33 deg C with a feeling of comfort over a wide range of outdoor temperatures.

As long as man is unprotected he will have to respond to low and high temperatures through a change of his energy intake, in order to maintain his stored heat. If he can afford to pay for the energy required to provide him with insulation and heating or cooling he is relieved from the adjustment through energy intake. This is the case today for most of the populations in the temperate climate. This situation could be reversed in the future if the means to pay for this sort of luxury or the energy itself (food) became less readily available.

The effect of climate on the energy requirement can be seen when similar groups of people with identical occupations are compared in two different climates. The daily energy intake of Indian soldiers near sea level is reported to be 3 780 kcal and at altitudes above 4 000 m 4 380 kcal 26. In the lowland the mean maximum temperatures are 30 to 41 deg C and at altitude 13 to -9 deg C, while the mean minimum temperatures are 7 to 21 deg C in the lowlands and -5 to -19 deg C at altitude. For comparison with another population, the energy requirement of native Indians aged 20 to 29 years in the High Andes at 4 000 m is 2 122 kcal for men and 1 677 kcal for women 27. This shows that among these native people the reduction of body heat production by means of clothing is high and the relative level of activity low. By way of contrast, the energy intake of 80 kg men at polar bases is 3 400 to 5 000 kcal, with a food fat content of 36.5 to 43 per cent 28.

Besides energy requirement the safe level of protein intake, that is "the amount of protein considered necessary to meet the physiological needs and maintain the health", has to be considered. It was found that in hot climates heavy sweating may result in a high nitrogen (N) loss, particularly among non-acclimatized persons. Among the indigenous population N loss through the sweating skin may be twice as high in a tropical climate as in a temperate climate. But this increased skin N loss is at least half compensated by a decreased urinary N loss.

Climate may create a higher demand for certain component elements of food. Examples are the higher Vitamin D requirements at high latitudes because of the low UV radiation and the larger iron requirements at high altitudes because of the increased erythropoiesis.

3.2 Growth and development

The human fetus is well protected against direct climatic influences. Birth weights of single-born children depend largely on the size and stature of the mother, her nutritional state, nutrients, diseases and, to an unknown small extent, climate. In north Europe the mean weight at birth is 3.3 kg. Groups weighing 2.9 - 3.2 kg include infants in Asia and Africa, and infants of American-Indian tribes weigh about 3.6 kg 29. At sea level in Peru mean weights between 3.3 and 3.6 kg are recorded; at altitudes above 3 000 m the birth weights are 6.3 - 15.7 per cent lower 30. The frequency of low-birth-weight infants at high altitude in Peru is 10 per cent while it is 24 per cent at comparable altitudes in new settlements in the United States. This is considered to be an expression of a more complete altitude adaptation of the Peruvian than the white American population 31. A strictly seasonal change of birth weight, where it exists, is more closely related to nutrition than to climate.

In extreme altitude climates sexual dimorphism (characteristics distinguishing between sexes) is considerably reduced when compared to sex growth curves at low altitude [30]. The alteration in the genetically determined patterns of sexual dimorphism can serve as a measure to determine the degree of suffering of a population from a strong climatic stress such as hypoxia, as long as nutritional deficiencies are eliminated. A significant retardation of development is observed in 15-month old infants under hypoxic conditions in Peru [30]. Also under the same conditions sexual dimorphism in adipose tissue disposition does not begin until about 14 years of age; and boys are more disrupted from their normal growth pattern than girls [32].

Climate, except for the hypoxic conditions discussed above, seems to have a minor effect on overall growth [32]. There is, however, a marked seasonal growth velocity for both sexes at all ages. In the northern hemisphere maximum increment is found between September to November, which can be up to 5 times higher than the minimum increment in spring between March and May. During the half-year period from September to February two-thirds, and from March to August one-third of the annual weight gain occurs. Height growth follows the opposite pattern: 55 - 57 per cent is made between March and August, with a mean growth rate in March, April and May, which is 2 to 2½ times that from September to November. However, the individual variations from the mean growth curves are wide. The mechanisms responsible for the seasonal variation of increment are not known [32]. The length of daylight has been considered as a possible stimulant in spring. The hormonal secretion of the endocrine glands may play a role, and this is also affected by temperature. The increased activity of the thyroid gland at low temperatures has been related to growth rate, but at low temperatures the increased caloric intake may be diverted from growth to heat production.

The age at menarche often serves as a clearly defined stage of development, though a wide range of variation exists in samples (standard deviation being about 2 years). The earliest mean ages reported are 12.4 years (Cuba) and the latest 18.8 years (New Guinea) [33]. A seasonal fluctuation with a higher incidence of onset of menarche in spring and summer was found among Finnish girls. Nutrition and the length of photoperiod seem to have an effect in this last example. A shift to an earlier age of menarche in Europe from 17 years in 1830 to 13 years of age in 1960 has also been found on other continents [34]. The role played by climate in the regulation of the age at menarche is unknown because a host of factors is involved, and it is impossible to disentangle and place them in a hierarchical order.

3.3 Fertility

Reproduction of man is favoured by the feature that the male has a continuous sperm production over a long period of his life and the female is polyestrous. Climate affects the reproductive fitness by a general or seasonal suppression of fertility. Evidence for differences between races and ethnic groups does not exist.

3.3.1 General suppression of fertility

From sea level up to 4 000 m altitude in Andean populations of Peru there is a significant decrease in the number of children under 5 years of age (Figure 5)

[35]. The conception rate of native high-altitude groups after migration to low elevations is higher than at high altitude and higher than the conception rate of low altitude natives. This increase of fertility of downward migrants at low elevations is understood to be due to the release from hypoxic stress. Women of Quechua populations and other Andean communities native to altitudes of 4 000 - 5 000 m complete 6.7 to 7.5 pregnancies by the age of 45 years when menopause sets in. Fertility was found to be highest in the fourth decade before menopause. The high fertility rate over the entire female reproductive period is achieved by various communal adjustments: pregnancies before marriage, formation of unions to include unmarried women and frequent remarriages [35].

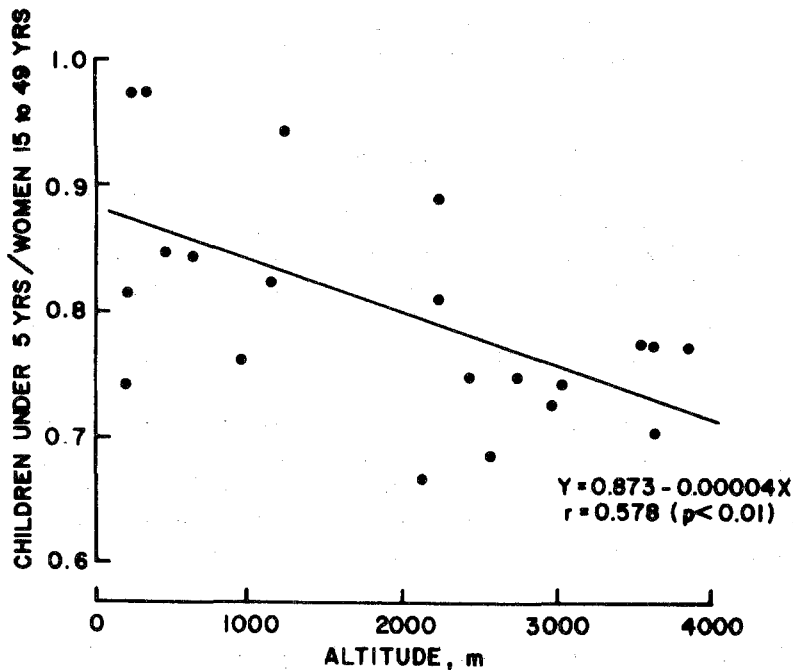


Figure 5. Fertility at altitudes up to 4 000 m in 21 Peruvian provinces (Source: [35]).

3.3.2 Seasonal variation of fertility

A seasonal change in fertility is observed in every climate. The change follows a circa-annual pattern, often with minor peaks and troughs. The maximum conception rate occurs in winter in southern India, South Africa, northern Australia and India, in spring in the middle and southern Europe, the southern United States and the near East, in summer-autumn in northern Europe, Canada and northern United States, and in autumn-winter in the more seasonal areas of the Asian tropics and sub-tropics [36, 37].

In most countries there is a negative correlation of the conception rate with mean monthly temperature. For Hong Kong the correlation is $r = -0.96$ in urban and $r = -0.95$ in rural areas. The maximum fertility is at 15 deg C, it declines at 21 deg C and is suppressed at and above 27 deg C [38]. At latitudes between the equator and the tropical belt there is only a small difference between the mean temperatures at which the highest and lowest conception rates occur. In Ceylon and Bombay the maximum fertility is between 26 deg C and 28 deg C and the minimum between 22 deg C and 27 deg C. In the low latitudes between 23° and 40° the maximum occurs between 9 deg C and 19 deg C and minimum between 22 deg C and 29 deg C. At high latitudes over 40° maximum conception exists between 16 deg C and 21 deg C and minimum between -3 deg C and 15 deg C. Two minima are usually found, one before and one after a summer-autumn peak. There are exceptions such as in Kansas, in the midwest of the United States, where the highest conception is in winter at -10 deg C or lower. In England the maximum conception is at 14 deg C and the minimum at 1 deg C or 7 deg C [36].

The seasonal changes between maximum and minimum fertility show wide variations. In England the total change is 8 per cent, in New Zealand 26 per cent and in Hong Kong 30 per cent. In Europe the seasonal change in the majority of countries is 20 to 25 per cent. Higher seasonal changes occur in the hot dry and hot wet tropics. Louisiana, USA, has over 30 per cent and Bombay over 50 per cent. At mean monthly temperatures above 25 deg C humidity contributes to the heat stress, and this may explain the marked suppression of fertility during the monsoon in India [36].

The patterns of seasonal change of temperature and conception rate are not identical. This excludes the length of photoperiod as a strong regulating factor of fertility in man. Though, there is a minimum of fertility in winter in Sweden, in Alaska with equally long winter nights the conception minimum is in spring. The winter minimum fertility occurs also in Germany and England which have shorter winter dark periods than in Sweden.

During the last 30 years changes in the seasonality of conception rates have occurred in most industrialized countries [36]. The main changes of fertility in the whole United States were:

- (a) Flattening of the amplitude of the winter maximum, with extension over a wider period.
- (b) Occurrence of the summer minimum 1 to 2 months earlier and more pronounced.
- (c) Flattening of the amplitude of the late winter or spring trough.

The seasonal flux is influenced by a number of factors, such as season of marriage, religious feasts and holidays, harvest time, nutrition, living conditions and economic development.

The acrophase of the conception maximum has implications for the mortality of infants. If the maximum of births coincides with the unfavourable climatic season of the year a high mortality of infants can be anticipated. For example, with a maximum of births in summer in the United States infant mortality rises significantly during heat-waves [39].

3.3.3 Fertility and population size

It appears that fertility of a community is regulated largely by mortality. As long as mortality rates are high all reproductive capacities seem to be utilized. When fertility increases and at the same time early mortality decreases due to change of climate, migration, or improvement of general health, nutrition, and living conditions a rapid population increase occurs. It will take some time, perhaps up to a generation, until processes begin to operate to adjust the conception rate to achieve a population that can be guaranteed full nutrition and well-being. A reduction of the fertility rate has become necessary in many countries after the elimination of formerly high early mortality rates in order to restore the balance between populations and nature. The present decline of birth rates in most western countries and some countries in Asia seems to occur independently of climatic changes.

However, should total mortality increase with a significant decrease of populations due to striking climatic changes, pests, or other causes, conception rates will probably rise again. Adverse effects of climate act as a stimulus to fertility to guarantee reproduction of the race.

3.4 Dwelling

The various envelopes which man utilizes to protect his body against the direct impact of the natural climate are grossly classified into clothing and housing. Clothing offers a large choice of materials for insulation and protection that is readily adjustable to the momentary requirements of man. Dwellings provide a protected space, are temporary or permanent fixtures, and can be equipped with extensive technical installation to stabilize indoor conditions.

Dwellings should provide comfortable thermal conditions with a small range of variation and daily change. They achieve an amelioration of the outdoor climatic conditions, even if the mean values do not match the comfort temperature, as in the Eskimo igloo. Comfortable temperatures in the northern region of the USSR are 21 - 22 deg C, in the temperate regions 18 - 20 deg C and in southern regions 17 - 18 deg C 40. In England the comfort range is given as 15.5 - 17 deg C while in the United States 22 deg C is recommended 41. Optimum classroom performance in 11 to 16-year-old children from 1966 - 1968 in England was at 15.8 deg C for boys and 16.1 deg C for girls. The temperature in the classrooms ranged between 11.7 and 25.0 deg C 42. Due to the seasonal adaptation of man winter comfort requirements are commonly lower than those in summer.

Comfort temperatures based on field studies in the tropics were 26 deg C for Calcutta, Nigeria and New Guinea, 27 deg C for Singapore in 1953 and 28.5 deg C in 1959. The comfort temperatures for different national-geographic groups with thin clothing and sedentary activity are 25.6 deg C for Americans, 25.4 deg C for Danes and 26.2 deg C for people from the tropics 43.

Comfort temperatures in dwellings are based on subjective assessments. They can be modified by clothing, activity, humidity, air movement and radiation 19.

Cooling of dwellings at night during the hot season is important for the regeneration of indoor conditions and to avoid heat accumulation due to heat production by its occupants. The close placing of buildings in modern cities has given rise to the formation of "heat islands", where even outdoor life can be more rigorous in summer than in nearby rural areas 44. There are higher mean temperatures during the day and night and delayed and reduced cooling of the buildings at night. The optimum of comfort is achieved with air conditioning in modern buildings to keep a standard temperature during all seasons throughout the year. It is, however, maintained with the consumption of large quantities of energy and a high release of waste heat, which contributes to the heat island effect. The acute dangers of heat and cold waves for man's health have now been largely eliminated for those who can afford to live in artificial environments.

3.4.2 General considerations

The value of dwellings is unquestioned as man's only possibility to establish stable comfortable conditions within a narrow space around him. The recent elaboration of artificial environments represents the final stage of a long cultural and technological development and may appear to satisfy man's desire for well-being. However, the accelerated application of technology in dwellings has already gone beyond the basic needs of populations. The individual at risk is better protected than ever before in air conditioned buildings, and as a result of the value of climate variations as a resource for the maintenance of physical fitness and a stimulus for seasonal adaptation of a population has been reduced. It has also resulted in a loss of experience in the appropriate behaviour towards unusual climate, and a frightening dependence of people in highly industrialized countries on technology and energy supply.

3.5 Working capacity, sport, travel, migration

Man has a high working capacity, which is necessary for his life support. The extent to which he can use this capacity depends on the prevailing climatic conditions, as there are limits to heavy physical work performance in hot climates when the heat production is high 45. The working pattern will have to be adapted in such a way that periods of work are interrupted by pauses to avoid or recover from overheating. High work performance over periods of several hours are achieved in comfortable temperate climates, and this can be further increased in modern industries by providing optimal conditions for the task in temperature- and humidity-controlled indoor climates 45, 46.

The working patterns in most outdoor and indoor occupations that have been developed in cool temperate climates are of high efficiency. They are, however, unsuitable for hot or very cold climates and high altitudes. Through life-long adaptation populations will work out the particular working patterns which are best suited for activities in their native climate and in this way will set their own standard. There is no such thing as a universally valid working pattern. It follows that in many populations, particularly in rigorous climates, work performance remains below the potential working capacity. Under such conditions an enforced increase of work performance would lead to early exhaustion and is deleterious to health. According to the heat balance equation, the more the heat dissipation is impeded in warm environments the more the physical performance capacity will be suppressed as the body heat storage increases.

Sport is a form of voluntary work performance for recreation and competition. Performances can be pushed to the limits of working capacity in a particular discipline. The choice of the sport discipline and the preference for certain sports in particular populations and countries again is related to the prevailing climate. Endurance sports such as long distance running are unsuited for hot climates because of high heat production in the body and the impeded heat dissipation requiring high sweating rates. Swimming is hampered in cool climates because of the increased heat loss in cold water. Olympic competitions demonstrate how the limits of human performance depend on the climate. During the 1968 Olympic Games in Mexico City at 2 400 m altitude the previous running records for short distances were broken while those for long distances were not reached 47. In the first case the reduced oxygen availability was not limiting over the short exercise time while the reduced air resistance favoured the athletes. Over long distances hypoxia became the major limiting factor.

Special climatic features have been used to facilitate and improve the high level of training required in competitive sports. For example, training and mid-altitudes provides a higher resistance to hypoxia which is advantageous for maximum performances at low elevations.

Two important forms of activity which involve change of climate are travel and migration. Travel is commonly characterized by rapid change, migration by slow change from one climate or season to another. The strain for the traveller may be large if his native climate and the climate in the area of his visit are distinctly different or enhanced by the contrast of season. Travel is in the majority of cases restricted to the age groups of high adaptability.

Migration can be voluntary, as in the case of nomadism, or enforced, as in evacuation after famine and war. For nomads migration is an adaptation of life to arid desert regions with a long tradition. The routes are planned on the basis of empirical knowledge of climate conditions over wide areas and follow a definite pattern. The nomads' migration starts off with the onset of rain and follows the rainy season as soon as grass provides food for the herds. They return to the dry area where they live most of the year afterwards if the crop of grass lasts them for the rest of the year. Migration is considered to be an optimal way of obtaining food from arid desert areas and avoiding overgrazing and the hazards of desertification in marginal zones. (See also overview papers by Oguntoyinbo and Odingo and by Mattei.)

Nomads are acclimatized to the climates along their routes by a complex physiological, behavioural and cultural adaptation. Enforced migration required more drastic adaptation, because different working patterns suitable to the new climate may have to be acquired while the traditional patterns must be abandoned. There will be more temporary hardships, strain and increased mortality among the age groups at particular risk and the sick of the population concerned. Enforced migration is a complex ecological, sociological and psychological process leading to such a high activation of adaptive reserves that the change of climate in conjunction with all the other changes involved is tolerated remarkably well. Enforced as well as voluntary migration of populations has occurred on a large scale many times in human history. It will occur again in the future if man is forced out of areas

because he cannot be provided with enough food for subsistence or because the climate becomes intolerable.

4. Climate as a direct cause of disease

If man is suddenly exposed to extreme deviations of climate which exceed his adaptive capacity his entire organism or parts of it may suffer. In this case one may speak of the direct effects of climate as a cause of disease or death. One group of direct effects are injuries which result from inappropriate protection of susceptible parts of the body in an unfamiliar and rigorous climate. Injuries occur soon after exposure and can terminate in death. The survival time of nude or clothed man on exposure to extremely high or low temperatures is from a few minutes to a few hours (Figure 2).

Another group of direct effects results from insufficient adaptation of individuals when rapidly moved into a new climate strikingly different from that to which they are acclimatized. In these circumstances individuals will suffer from diseases of maladjustment. A summary of disorders resulting from direct influences of climate is presented in Table 6 4, 46. In every case of direct effects of climate two facts are decisive: first, the relative and absolute strength of the stimulus, and second, the exposure time.

4.1 Injuries

The list of injuries is short. They are limited to the skin, the eyes and prominent parts of the body such as ears, nose, fingers and toes. Effective factors are UV radiation, high light intensity, and low temperature or high chilling power. UV effects are aggravated when the skin is wet with sweating in hot climates, and also by poor pigmentation. Dark pigmentation of the skin provides protection against sunburn, and also the blinding effect of light is attenuated by dark pigmented sclera. Such injuries are however common in races with little pigmentation of the integument. Anoxia occurs on exposure to altitudes above 7 000 m.

4.2 Maladjustments

The multiple diseases of maladjustment to heat are frequent among newcomers from cold and temperate climates but also occur among populations indigenous to a hot climate. Several of these disorders can lead to death, such as heat stroke or the various forms of fluid and salt exhaustion, if remedies are not applied rapidly. Disorders of the skin may be transitory, such as prickly heat, or permanent as in the case of congenital sweat gland deficiency. Individuals subject to the latter are not fit to undergo extensive heat exposure.

Psychoneurotic disorders were formerly collectively named tropical neurasthenia 48. This disease has gone through many changes of aspect, and it is now seen as a "climate disease" due to maladjustment. Psychological disturbances can certainly occur in labile individuals, but this will also be possible in cold and high altitude climates.

Table 6

Disorders due to a direct effect of climate (Source: 4, 46/)

	Injuries	Maladjustments
Ultraviolet radiation	Sunburn Sun-blindness (solar retinopathy)	
Heat		Systematic disorders Heat stroke, hyperthermia Circulatory deficiency heat exhaustion Water deficiency heat exhaustion Salt deficiency heat exhaustion (heat cramps) Anhidrotic heat exhaustion Psychoneurotic disorders Mild heat fatigue Chronic heat fatigue Skin disorders Prickly heat Anhidrosis Congenital sweat gland deficiency Dermatitis or excema
Cold	Frostbite Chilblains Snow-blindness	Hypothermia Contact dermatitis Cold exhaustion Autoimmune hemolytic anaemias (Cold agglutinin disease)
Altitude	Anoxia	Acute pulmonary edema Mountain sickness Sickle-cell anaemia

Maladjustments in the cold are less numerous 49/. Physiological failures such as hypothermia can be treated, while inherited susceptibilities among certain African populations such as auto-immune hemolytic anaemia, which occur with cold exposure, prohibit life in cold climates 50/.

Maladjustments at high altitude, acute pulmonary edema, and mountain sickness occur soon after arrival at altitudes of about 4 000 m due to hypoxia, often in conjunction with cold exposure 51/. The best remedy besides breathing oxygen is the immediate removal of the patient down to lower altitudes. In such cases a more gradual adaptation to altitudes is indicated. Mountain disease also occurs in older people of native populations as an expression of decompensation of adaptation mechanisms. High incidences of mountain disease has been observed among soldiers of expedition corps who were transported by air from warm sea level elevations to cold high

altitudes in the Himalaya mountains. Among expedition troops it is general knowledge that they have two opponents: the enemy and the climate.

5. Non-communicable diseases

In many human diseases climate may contribute directly or indirectly to the appearance of the disease, aggravate pain and suffering or accelerate death. As the majority of diseases is of multifactorial origin including various failures of homeostatic regulation, the importance of climate in the chain of nosogenic factors which leads to the final breakdown of the system is not always easy to ascertain. To date the elucidation of the role of climate in diseases has been neglected because all attention has been focussed on the body and too little on the environment.

5.1 Mortality

Correlation studies of mortality rates with climatic data began in the middle of the nineteenth century when the first vital statistics became available. In England as early as 1840 Dr. William Farr reported a sharp rise in mortality during cold and foggy days 52 and in 1843 Guy found high death rates in connexion with hot weather 53.

A thorough evaluation of mortality rates in New York City from 1882 to 1888 by Huntington 54 showed that there was a circa-annual rhythm in mortality, with a high amplitude and peak incidence in the summer months July and August. An evaluation of total mortality rates in the City of Chicago from 1867 to 1925 (Figure 6) by Goldsmith and Perkins 55 revealed that during these nearly 60 years the circa-annual rhythm had remained while two significant changes had occurred:

- (a) a phase shift of the peak incidence from the summer to the winter months December to March;
- (b) a reduction of the amplitude.

The monthly total mortality rates from all causes of the entire United States during 1951 - 1960 shows a similar cycle, with the maximum of mortality during December and January and the minimum during August and September 56. Kutschenreuter 57 compared similar data for the decade from 1949 to 1958 of the cities New York, Cincinnati, and Los Angeles with mean monthly temperatures (Figure 7). The inverse relationship of the two cycles reveals a negative correlation between total mortality and temperature. The high winter mortality in temperate climates is observed in both the northern and the southern hemispheres (Figure 8) 55, 58, 59.

In a high altitude population in Peru (15°S Lat.) the monthly death rate from 1950 to 1969 showed a maximum from November to January, which was about 60 per cent above the minimum from April to June. The maximum coincided with the height of the rainy season and the minimum with the harvest time 60.

The dynamics of the shift of the peak mortality from the summer to the winter season in Japan has been thoroughly investigated by Momiyama 61 (Figure 9). Covering the period from 1899 to 1973, Momiyama noticed a flattening of the summer mortality peak up to 1950 while a winter mortality peak began to build up. In the following years the amplitude of the winter mortality peak rose steadily until 1970, and it has decreased since then while a moderate summer peak has reappeared. In 1973 there was a circa-semi-annual rhythm, with the main peak in winter and a minor peak in summer.

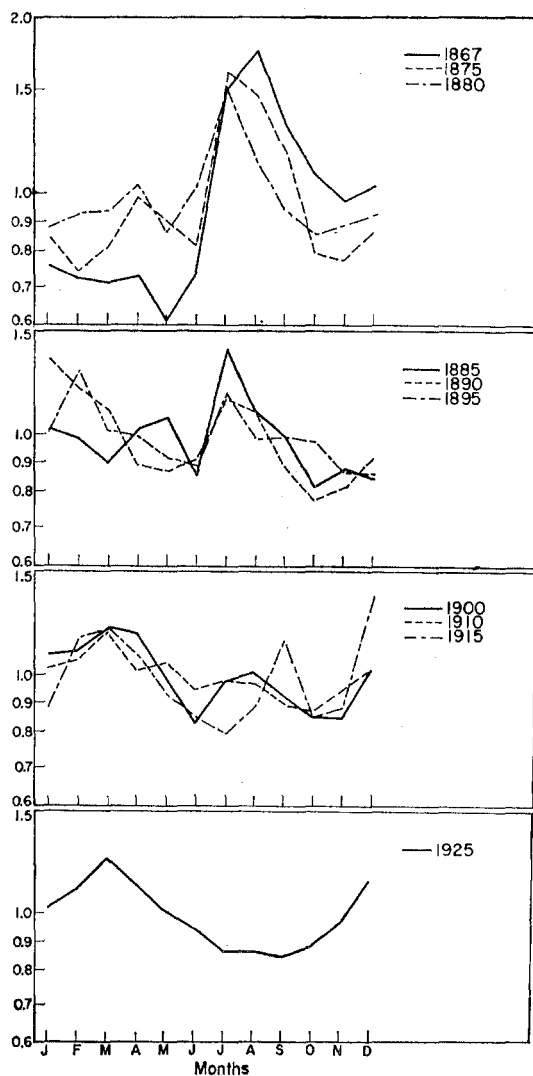


Figure 6. Monthly rate of total mortality in Chicago from 1867 to 1925 (Source: 55)

In the United States a maximum winter mortality rate (1951-60) was found for those suffering with cerebrovascular disease, arteriosclerotic heart disease, non-rheumatic chronic endocarditis and other myocardial degeneration, and diabetes mellitus. No seasonal change in mortality rates was observed for malignant neoplasm (morbid growth). Incidentally, mortality from motor car accidents was highest in December and lowest in February, and mortality from suicide highest in April and lowest in December (Figure 10) 56.

In 1952 De Rudder 62 compiled tables of monthly distribution of morbidity and mortality from various diseases. This allowed the singling out of all diseases with a seasonal incidence and the calculation of the phase on an annual scale.

De Rudder used earlier vital statistics obtained before the sulpha drug and antibiotic era. The majority of the diseases in his tables belong to the class of communicable or infectious diseases, and only a few to systematic diseases (cardio-vascular) or deficiency diseases (rickets).

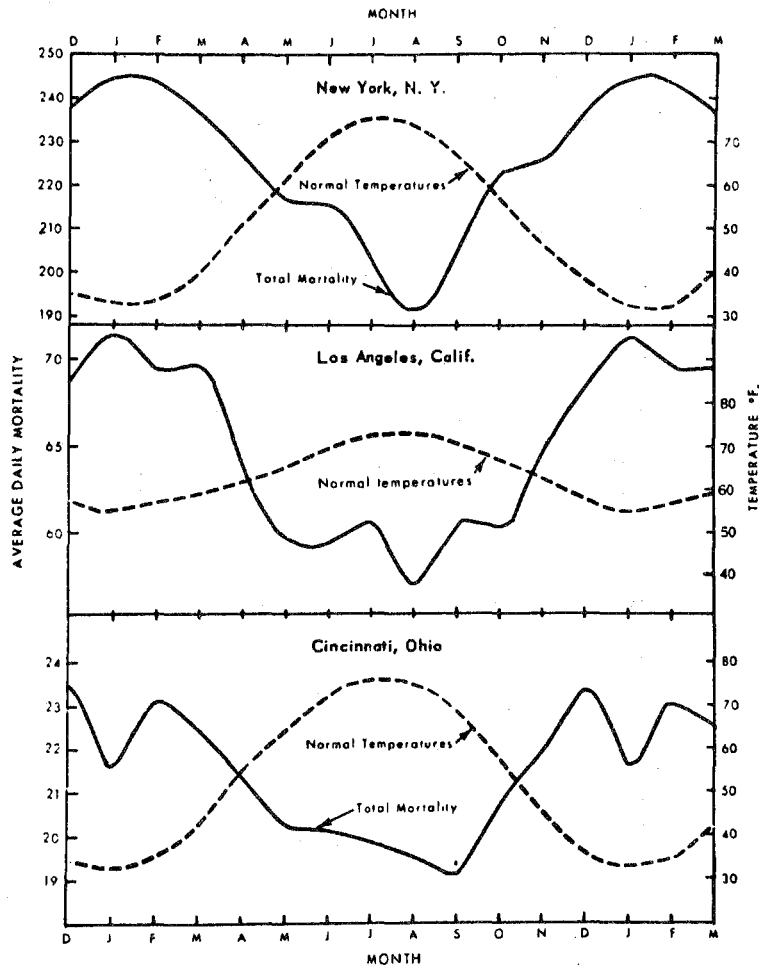


Figure 7. Mean daily total mortality and temperature in 3 cities in the United States (Source: 57).

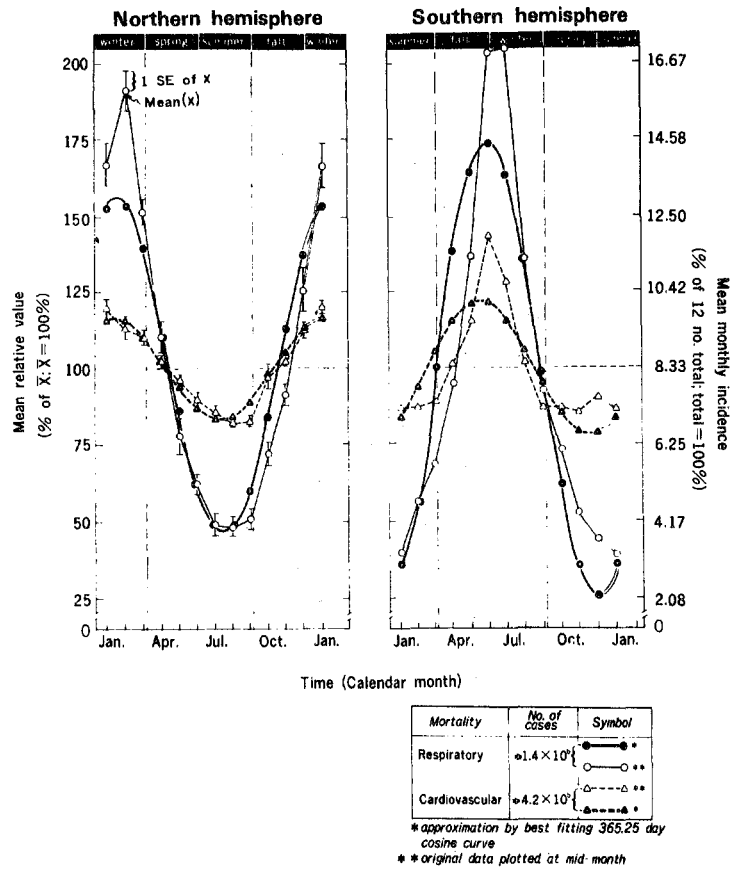


Figure 8. Circa-annual chronogram of human respiratory cardiovascular deaths in the northern and southern hemisphere (Source: 58).

DeRudder's phase maps of diseases have been elaborated into disease calendars by Momiyama 61. An example of a disease calendar in Figure 11 summarizes the death rates in the 1950s for 14 diseases in three countries. In Great Britain mortality rates from all diseases were highest during the cold winter months. The 4 main causes of death were pneumoniabronchitis, heart diseases, cerebrovascular diseases, and cancer. In Egypt the maximum mortality rate for the majority of diseases, in particular of gastroenteritis, occurred during the summer months, and only for pneumoniabronchitis was it from December to May; cerebrovascular disease played a minor role. In Japan there were clearly marked winter mortality peaks for some diseases as in Great Britain, but there were also summer mortality peaks from other diseases similar to the situation in Egypt.

The present contention is that countries with a high standard of industrialization show winter peak mortality chiefly from non-communicable diseases, and this has accompanied decline or eradication of high mortality rates from communicable diseases, while developing countries in the early stages of industrialization are characterized by high summer mortality rates. Industrialization implies a host of other related or contributory factors, such as adequate nutrition, a high standard of hygiene, living conditions, health services and medical care.

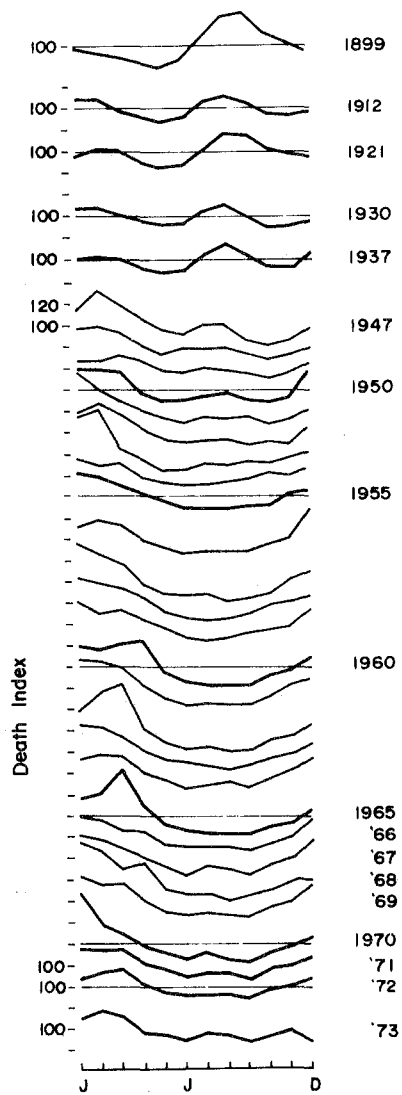


Figure 9. Change of pattern in monthly rate of total mortality in Japan from 1899 to 1973 (Source: 61).

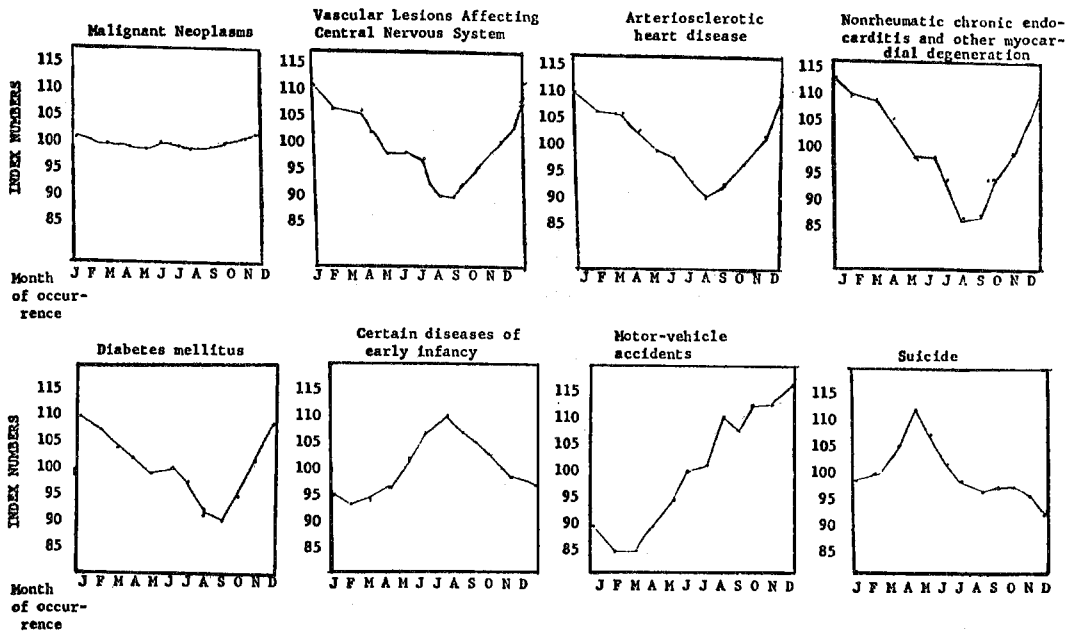


Figure 10. Mean monthly death rates from selected causes during 1951-60 in the United States (Source: 56).

The effect of those factors involved in improvement of the standard of living and health is demonstrated by the decline of the seasonal variation and incidence of infant mortality from pneumonia and bronchitis from 1952 to 1970 in Japan 63 as shown in Figure 12.

The shift in causes of mortality from communicable diseases to non-communicable diseases is demonstrated in Figure 13 64. From 1958 to 1972 the cumulative percentage changes of mortality from infectious diseases decreased more than 400 per cent in Columbia, 300 per cent in Singapore, and under 50 per cent in Sweden. In Singapore, as elsewhere, the striking decrease of mortality from infectious diseases is the result of the improvement of socio-economic conditions together with more efficient public health measures. During the same period the mortality from cardiovascular diseases had increased 600 per cent in Singapore, 300 per cent in Columbia and 500 per cent in Sweden. The decreased mortality from infectious diseases has caused a shift from early to late mortality and consequently a growing population of old people. In former times epidemics gave rise to seasonal mortality patterns in all age groups; now seasonal patterns have become limited to the age groups of poor adaptability.

A division of total mortality in New York City from 1949 to 1958 into 7 age groups showed that there are age dependent mortality curves (Figure 14) 57. A seasonal peak mortality existed for children under 1 year of age and adults older than 25 years. The amplitude of winter mortality increased with advancing age with the most pronounced circa-annual rhythm in the elderly of 65 years and older.

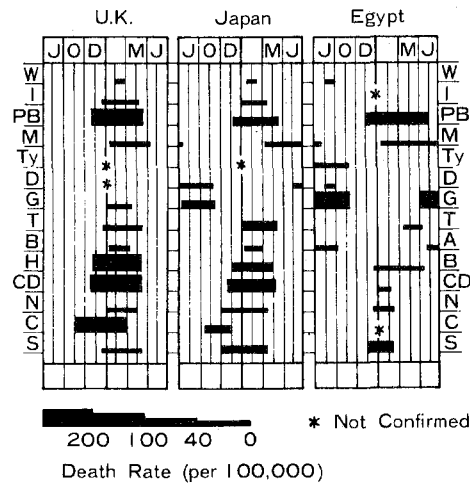


Figure 11. Examples of a disease calendar for 3 countries: United Kingdom, Japan and Egypt (Source: 61).

The death rates are classified into four grades:

0-40, 40-100, 100-200, and over 200, each indicated by the bar breadth. Diseases:

- | | |
|-------------------------|----------------------------|
| W Whooping cough | B Beriberi |
| I Influenza | A Avitaminosis |
| PB Pneumonia-bronchitis | H Heart Disease |
| M Measles | CD Cerebrovascular disease |
| Ty Typhoid | N Nephritis |
| D Dysentery | C Cancer |
| G Gastroenteritis | S Senility |
| T Tuberculosis | |

To summarize, the seasonal prevalence in morbidity and mortality from communicable as well as non-communicable diseases is a specific medical-biological problem of the man-climate relationship 65. There is a seasonal change in susceptibility to environmental hazards that can be demonstrated by continuous measuring of physiological parameters throughout the year 66. Consequently careful analysis will reveal some rhythmic change of mortality in every age group, though the amplitude will be low in the juvenile and young adults and high in the very young and very old.

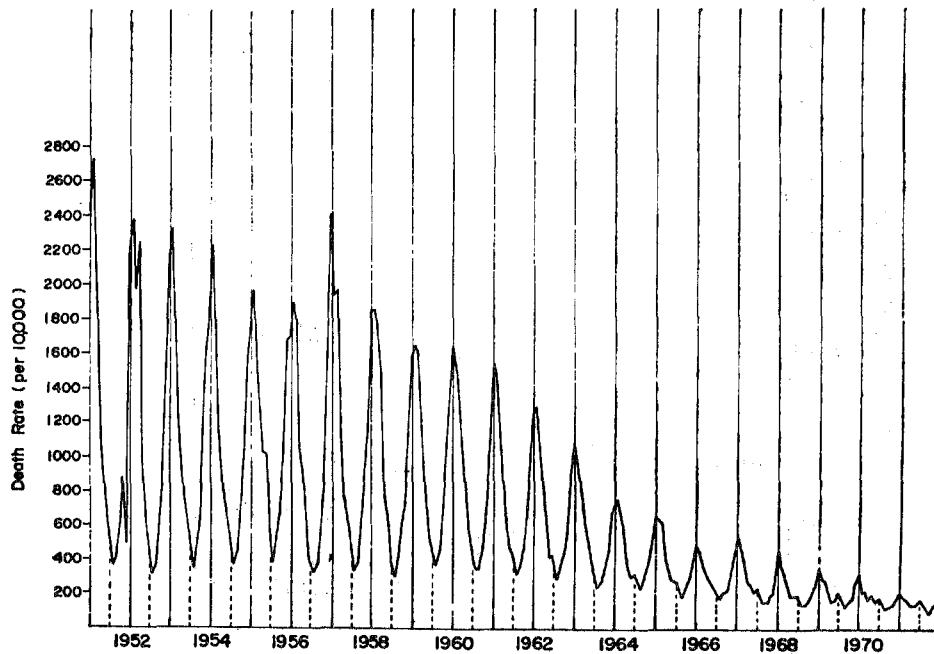


Figure 12. Change of infant mortality from pneumonia and bronchitis in the period 1950-1970 in Japan (Source: 63).

The age groups at risk require particular protection against climatic impacts. Where such protection is provided, as in industrialized countries with a high socio-economic standard, the seasonal prevalence in mortality rate begins to disappear. The phenomenon, which is now known as "deseasonalization", is demonstrated in 4 populations of 3 countries in Figure 15. For infants (under 1 year) and old persons (over 70 years) the seasonal fluctuations of mortality is still high in Japan while it is low in the whole of the United States as well as in New York City 61.

The high summer death index among teenagers (10 - 19 years) is largely due to death from accidents related to the vacation period.

5.2 Mortality and temperature

On the basis of an analysis of the mortality rates in New York in the latter part of the last century, Huntington 54 stated that there is an optimum temperature at which the mortality is minimal. Many correlation studies of mortality rates with mean monthly or daily temperatures demonstrate such a dependence of mortality on temperature 57, 61. The mortality index from arteriosclerotic heart disease in England and Wales (1958 - 1962) at mean temperatures from 2 deg C to 21 deg C (Figure 16) was highly significantly correlated with temperature, with a correlation coefficient, $r = -0.95$ 67.

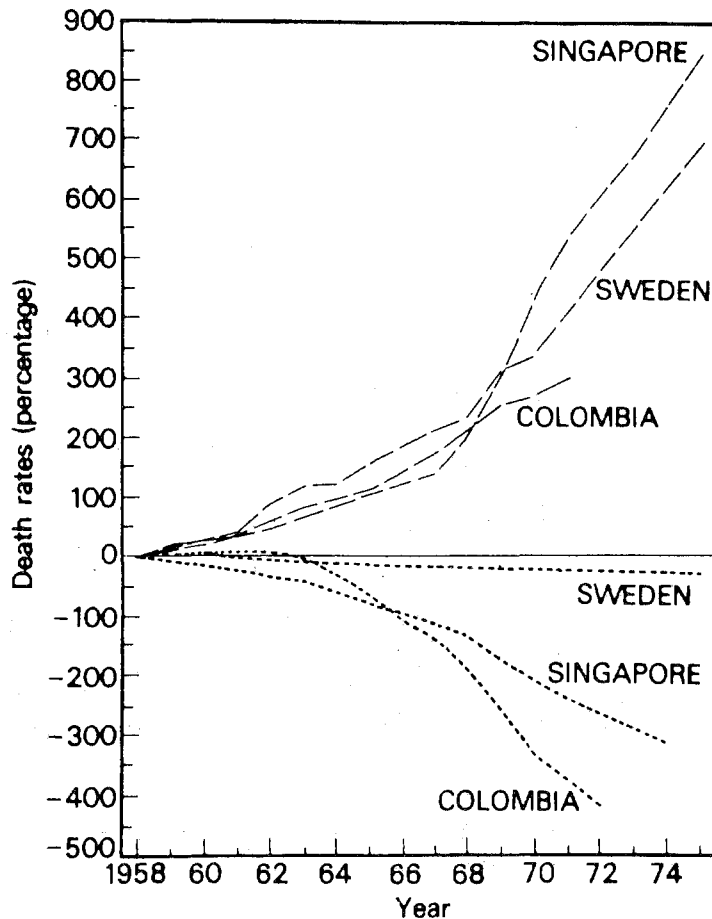


Figure 13. Cumulative sums of death rates in per cent of 1958 values in selected countries showing decrease of mortality from infectious diseases and increase from cardiovascular diseases (Source: 64).

The results of correlation studies over a wider span of temperatures for mortality from cerebrovascular disease in different countries is presented in Figure 17 61. In the case of Tokyo there is a negative correlation from 0 deg C to 24 deg C and a positive correlation from 24 deg C to 28 deg C. Hence, the minimum mortality risk existed at 24 deg C. For New York City the scatter at and above 24 deg C is large, indicating that there is some increased death susceptibility. Under well controlled winter living conditions the slope of mortality rates down to -4 deg C in New York City and down to -8 deg C in Sweden is nearly flat. In the cold climate of Hokkaido a steep negative correlation was found between 12 deg C and 23 deg C and a nearly flat slope from 12 deg C down to -8 deg C. The flattening of the winter mortality in Hokkaido for the colder temperatures is ascribed to the protection of man by the well planned room heating in that area 63. In general summer mortality peaks are seen in temperate climates with high summer temperatures.

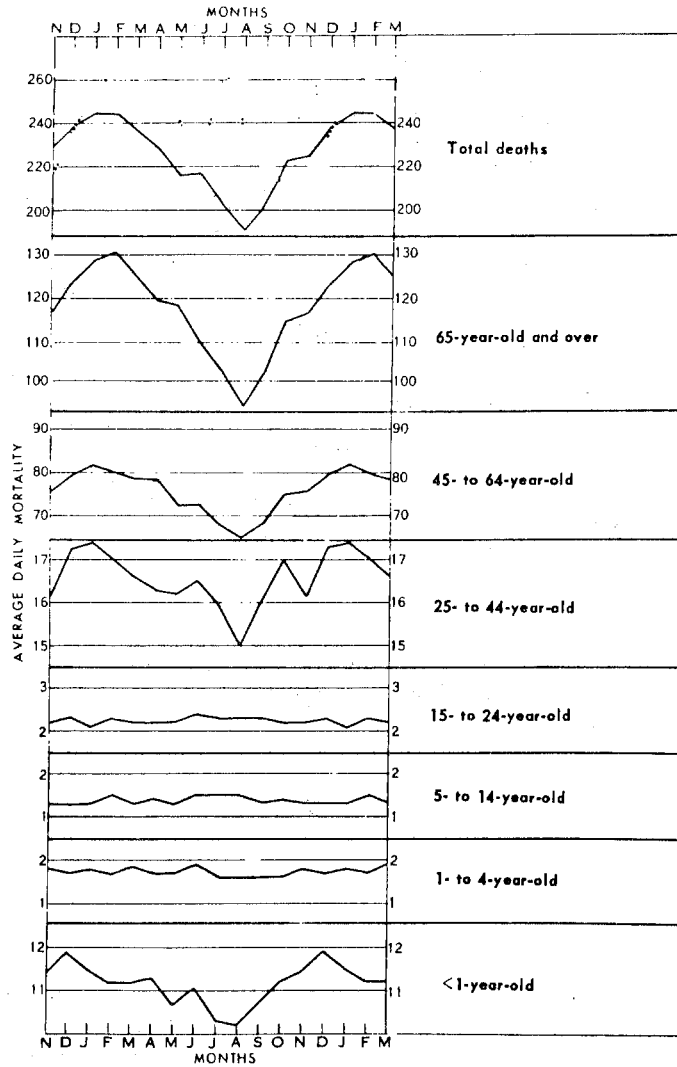


Figure 14. Daily total mortality by month for different age groups during the period 1949 - 1958 in New York City. (Source: 57).

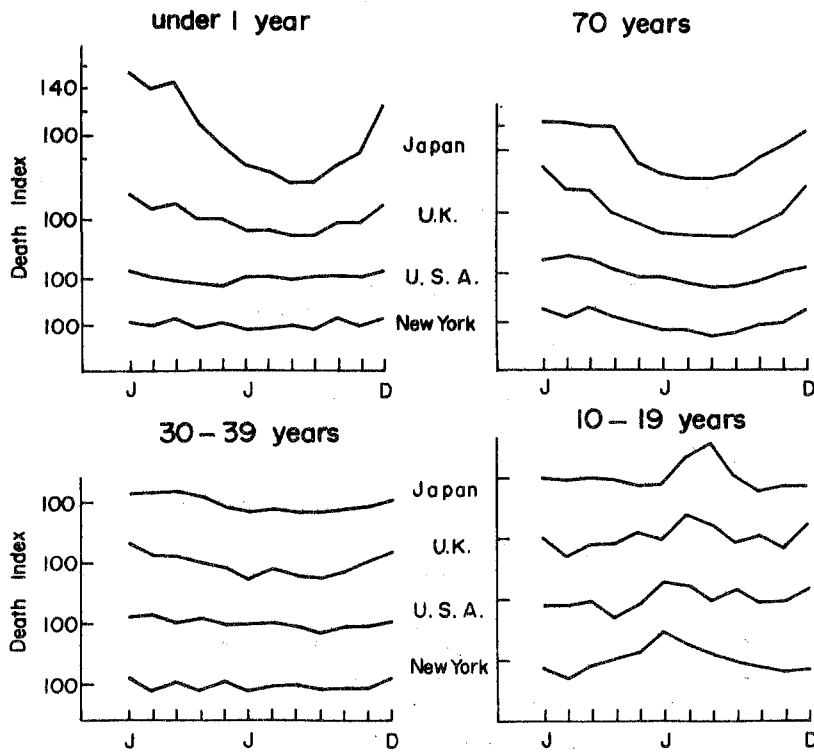


Figure 15. Mean monthly mortality rates for 4 age groups in 4 populations during the period 1958 - 1962 (Source: 63).

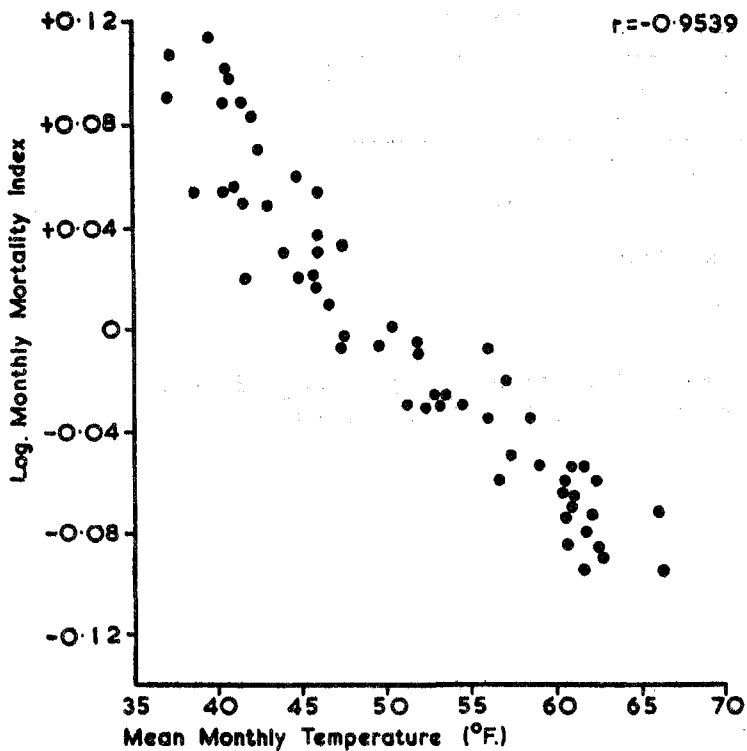


Figure 16.

Correlation between mean monthly mortality (log. monthly mortality index) for arteriosclerotic heart disease and temperature (Source: 67).

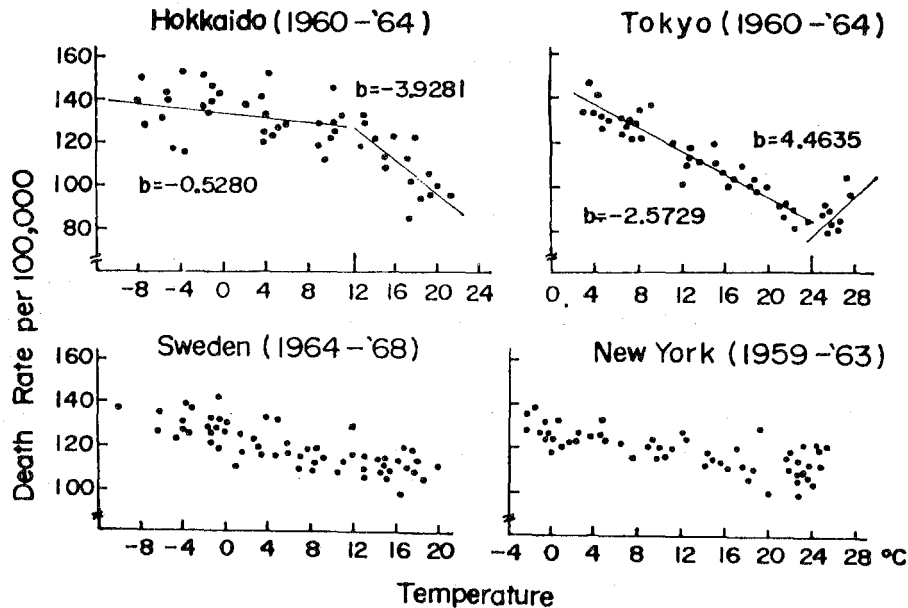


Figure 17. Correlations between mean monthly mortality rates for cerebrovascular disease in 4 populations (Source: 61).

The curve of the relationship between mean monthly temperature and mortality of Tokyo (Figure 17) resembles the curves found in human and animal physiology for the relationship between temperature and heat production, oxygen consumption, or subjective comfort. The temperature zone of minimum mortality corresponds to the thermoneutral zone, which is limited by the lower and upper critical temperature. Below and above these critical temperatures heat production increases and so does mortality.

The zone of minimum mortality can be widened with improvement of insulation by clothing and by life indoors with an artificial climate. This has been achieved with success in such places as New York, Sweden and during the winter in Hokkaido, as the flat mortality curves in Figure 17 have demonstrated. The widening of the zone of minimum mortality also existed for mortality rates from coronary heart disease and cerebrovascular disease in 32 metropolitan areas in the United States, of which 17 were in cool and 15 in warm regions. Mortality was consistently low between 15.6 deg C and 26.6 deg C. In cool climates mortality increased linearly below 15.6 deg C and in climates above 26.6 deg C. In hot regions a shift of the upper critical temperature from 26.7 deg C up to 32.0 deg C was observed 68. In the 3 cities in the United States shown in Figure 7 mortality was lowest during the warmest months in summer because the mean annual temperature remained below the critical temperature of 32 deg C. High winter mortality from diseases related to the vascular system seems to be typical of temperate climates with low winter temperatures. It must be anticipated that for the same group of diseases in tropical climates where heat stress is the prevailing climatic factor a high summer mortality will exist. Examples for this relationship are the moderate increases of mortality during the summer months for some years in Japan, demonstrated in the lower part of Figure 9. However, as long as detailed mortality statistics of populations living in hot dry and hot humid climates are not available, this high summer mortality is only partially proven.

Other climatic factors such as humidity, wetness, wind, and sunshine, can enhance the effect of temperature. The temperature of minimum mortality for aged and chronically ill people in Sydney, Australia is at 18.3 deg C for high humidities and 21.0 deg C for 50 per cent RH. For bedridden elderly people the zone extended from 21 deg C to 26.0 deg C 69.

In areas with wide climatic variation and regular heat waves during the summer months, as in the south-eastern states of the United States, high mortality rates are recorded following extreme increases of temperature. In 5 out of 13 years from 1925 to 1937 the summer weekly rates of mortality in large cities rose as high or higher than the mean January rate 70. An analysis of more recent mortality statistics for the years 1952 - 1967 showed that heat waves caused an appreciable number of deaths due to excessive heat in about half the states 39. In New York City the mean monthly number of deaths from certain diseases of early infancy showed a high amplitude, with peak mortality during high temperatures in July. In a careful analysis on infant mortality in Latin America from 1950 to 1970 highest mortality was correlated with cold and low humidity 71, and this finding was true for two chosen economic levels based on Gross Domestic Product. Where the economic levels were low infant mortality was relatively high in spite of favourable climatic conditions. The studies demonstrate the complex interrelationships between the many environmental factors with their fluctuating strengths.

Heat waves in temperate climates turn out to be a strong factor 39, 70. Death rates during the first heat wave are higher than during a second wave shortly afterwards, even if more severe and longer lasting. One explanation is that the population of highly vulnerable persons is depleted during the first heat wave, as they have died. Also precautions against the impact of heat have improved and some heat adaptation has developed.

5.3 Morbidity affected by meteorological factors other than thermal

Before the formation of Vitamin D in the skin under the effect of UV radiation was fully understood there was a high winter mortality from rickets. With the preventive administration of Vitamin D during the months with low intensity of UV radiation winter mortality from rickets has disappeared in the northern countries. Where children are traditionally protected from solar radiation as in some communities in Ethiopia high mortality from rickets can occur even in climates at low latitudes with maximum sunshine hours.

Repeated ultraviolet exposure can cause damage of the skin leading to skin cancer. The skin damage is facilitated in white populations with little or no pigmentation of the skin, as in northern European countries. No case of skin cancer has been reported among the black native populations in Africa despite intensive exposure of the entire body to the sun 72. As the protection against UV radiation imposes no difficulties for insufficiently pigmented individuals no major harm can be anticipated should the intensity of UV radiation increase in the near future as part of a climatic variation.

A large group of diseases with high seasonal morbidity rates are associated with allergies, such as asthma and hay fever. They are triggered off by allergens which are often products of plants during flowering and harvest time. It is not known to what extent heat and cold affect the sensitivity of the susceptible individual to the allergen and initiate an outbreak of the allergic disease 62. From various parts of the world it has been reported that cold acts as an asthmagenic 73.

On many occasions a direct relationship between suicide and climate is postulated (and this has been extended to an effect of climate on the incidence of mental diseases). The seasonal trend of suicides with a peak of mortality in spring has been confirmed repeatedly 56 (Figure 10). For monthly suicide deaths in Japan significant negative correlations have been found with atmospheric pressure and positive correlations with temperature and sunshine hours 37.

An unusual pattern of mortality rate also exists for motor vehicle accidents (Figure 10). The steady increase over the year from the minimum in February to the maximum in December indicates the complex relationship of these events with various ecological factors such as the change to the short photoperiod in winter, rain and frost affecting the road surfaces, and human or social factors.

6. Communicable diseases

Diseases are communicable if they are transmitted from one person to another by actual contact or contagion. The communicable diseases of man are due to the attempted colonization of his body by parasites of various species, e.g., viruses, bacteria, protozoa, helminths and arthropods. The parasite must penetrate into the body by the route to which it is adapted. The entrance routes are the alimentary tract, the respiratory tract and other mucous membranes, or the skin. Entrance can be achieved by force through bites of blood sucking insects. For each species of parasite there is a part of the body where conditions favour survival and multiplication. Man will respond to the specific and non-specific substances produced by the parasite with immunity to restrict their multiplication or alter the effects of the invasion. Immunity against parasites can be fully protective and long lasting or weak and of short duration. There is also a natural immunity that is inherent and independent of previous infections. Protection against infection can be induced with specific protective antibodies as passive immunity from the mother by transference or from another host by inoculation.

For their continued existence parasites require certain climatic conditions, in particular of temperature and humidity. Airborne parasites may die before they reach a new host under unfavourable climatic conditions. Other parasites transmitted by arthropods may need long enough periods of favourable temperature to complete an essential part of their life cycle. Parasites of man are found in every climate, but the majority of them is limited to the tropical climate.

With respect to climate, communicable diseases can be divided into contact and proximity or contagious diseases and non-contagious diseases 74. Climate plays a minor role in contagious diseases which are transmitted directly from man to man without an intermediary. They can spread to a greater extent in aggregated populations and small groups and to a lesser extent where men are widely segregated. Indirectly the incidence of contagious diseases is favoured during cold seasons when habitually people crowd into dwellings.

In non-contagious communicable diseases climate plays an important role due to its effect on the life cycle and survival of the parasite, on the life cycle of the vector, and on the route of transmission. Examples of contagious and non-contagious diseases are listed in Tables 7 and 8.

Table 7

Examples of communicable diseases: proximity and contact infections

Name	Incidence
Gonorrhoea	non-seasonal
Leprosy	"
Smallpox	"
Syphilis	"
Trachoma	"
Treponematoses	"
Tuberculosis	"
Bronchitis	seasonal
Enterovirus infections	"
Influenza	"
Measles	"
Meningococcal meningitis	"
Poliomyelitis	"

6.1 Contagious infections

The diseases of Table 7 are of world-wide distribution. The list could be extended with further diseases of more limited distribution. Diseases of the first group are transmitted by direct contact such as smallpox and trachoma, which are found throughout the world but are most prevalent in hot, dry areas of the tropics and sub-tropics.

Most viruses are harboured by man and epidemics occur at regular or irregular periods. Outside the host the parasites can survive for some time, but for most viruses knowledge of survival times is deficient. The death rate of influenza virus is high at 50 - 90 per cent RH and low at 15 - 40 per cent RH. For the poliomyelitis virus the inverse was found [75]. The smallpox-causing variola virus survived in crusts and in cotton 12 - 18 months at 20 deg C and 58 - 75 per cent RH. In bales of cotton at 30 deg C the virus has survived for 6 weeks at 84 per cent RH, for 2 months at 73 per cent RH, and for 3 months at 58 per cent RH. It is killed within 3 - 4 hours on exposure to direct sunlight. The survival of the virus is favoured by low humidity of the air [76].

Table 8

Examples of communicable diseases: non-contagious infections.

Associated with Low Standard of Hygiene		Insect-Borne Infections	
Name	Vector	Name	Vector
Cholera		Yellow fever	Mosquito (<i>Aedes aegypti</i>)
Typhoid fever	water-borne	Dengue fever	Mosquito (<i>Aedes</i> spp.)
Paratyphoid fevers		Malaria	Mosquito (<i>Anopheles</i>)
Bacillary dysentery	water-borne	Filariasis	Mosquito
Amoebic dysentery	water-borne	Wuchereria bancrofti	(<i>Culex</i> , <i>Mansonia</i> , <i>Aedes</i>)
Polyomyelitis		Loa loa	(<i>Chrysops</i>)
Trichuris trichiura		Onchocerca volvulus	(<i>Simulium</i>)
Enterobius vermicularis		Leishmaniasis	Sandfly (<i>Phlebotomus</i>)
Taenia saginata		Bartonellosis	Sandfly (<i>Phlebotomus</i>)
Taenia solium		Afr. trypanosomiasis	Tsetse fly (<i>Glossina</i>)
Diphyllobothrium latum		Amer. trypanosomiasis	Bug (<i>Triatoma</i> , <i>Panstrongylus</i>)
Ancylostoma duodenale		Epidemic typhus	Louse (<i>Pediculus</i>)
Strongyloides stercoralis		Murine typhus	Flea (<i>Xenopsylla</i> , <i>Bdellonyssus</i>)
Schistosoma haematobium	aquat. snail	Tick-borne typhus	Tick (<i>Dermacentor</i> and others)
Schistosoma japonicum	aquat. snail	Mite-borne typhus	Mite (<i>Leptotrombidium</i>)
Tetanus		Louse-borne	
		relapsing fever	Louse (<i>Pediculus</i>)
Food poisoning		Plague	Flea (<i>Xenopsylla</i> and others)
Salmonella spp.			
Staphylococcus			
Clostridium welchii			

The virus diseases with seasonal morbidity are common in tropical as well as in the temperate climates. A 9-year study of WHO virus reports from 1967 to 1975 on fatal virus infections in the northern hemisphere showed that influenza A was by far the most frequently implicated virus 77. The maximum number of cases and deaths from influenza A infections is between October and March. Years with a very high incidence are followed by years with an extremely low number of cases (Figure 18). High morbidity from influenza A occurs not only during the cold season but also is aggravated by sudden climatic changes with cold spells.

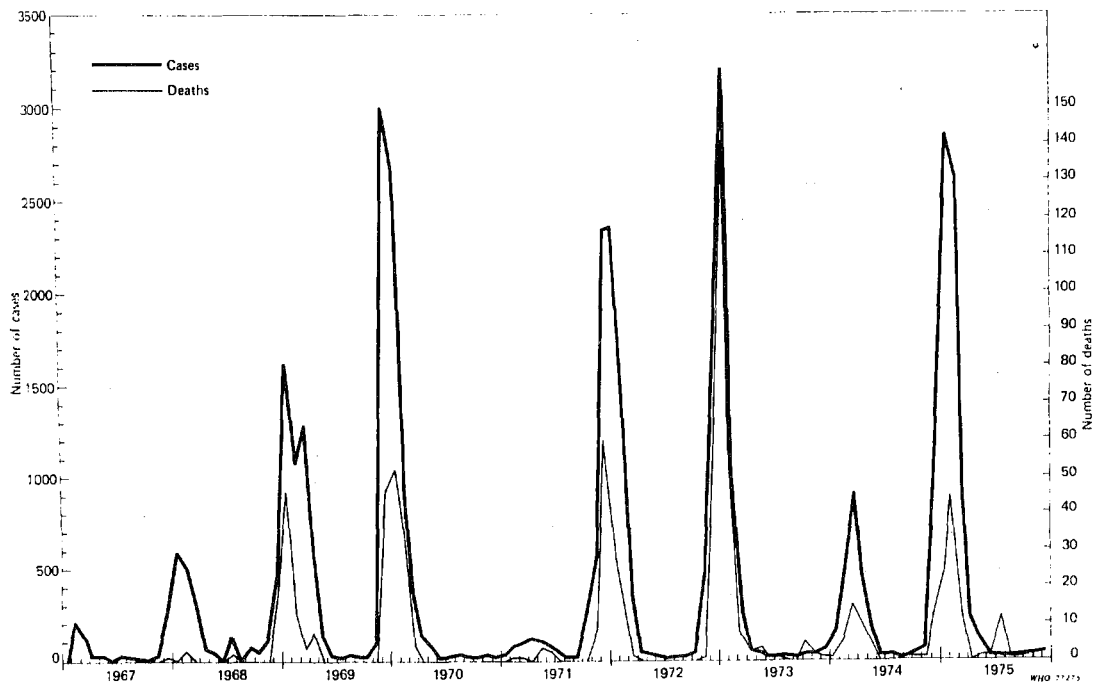


Figure 18. Number of monthly cases and deaths associated with influenza A virus infection in the northern hemisphere based on the investigation of specimen (Source: 77).

An inverse seasonal distribution of incidence is observed for infections from several types of enteroviruses. Infections are least common during the winter months in the northern hemisphere, but rise steeply during the summer months and gradually decline in autumn. In any one country more than one type of enterovirus becomes epidemic during the summer 78.

An example of a disease in a hot-dry climate with striking seasonal change of morbidity is meningococcal meningitis, which is very frequent in the African countries south of the Sahara desert. The highest morbidity rate is recorded during the months March and April. The rise of the morbidity curve begins about 4 weeks after the annual relative humidity curve is at the lowest level, and the maximum incidence rate is observed when the mean relative humidity is lowest (10 per cent RH). It is

thought that the dry winds affect the mucous membranes of the nose which facilitates the infection. When the rainy season begins the epidemic collapses abruptly ^[79]. The climatic variation in the Sahel zone during recent years inevitably affected the incidence and the seasonal pattern of the disease.

These examples may show that the daily and monthly temperatures of hot or cold seasons contribute to the occurrence of a virus disease. Whether climate acts on the virus or on the host or on both is not known.

6.2 Non-contagious infections

The biological patterns in non-contagious infections are complicated. The parasites have complex life cycles of which some phases take place in a temperature-conforming vector or medium and some phases in homeothermic hosts, both mammals and man. As long as the parasites are not in a homeothermic environment, ambient temperature and other climatic factors will affect them in any developmental stage of their life cycle. Such effects can be favourable or unfavourable. It makes little difference when the parasite is inside the transmitting insect host, for they are all temperature conforming organisms. The activity and abundance of insects is associated with the climatic conditions at the time and the population-changes with the climatic conditions in the previous months ^[80]. The effective temperature describing man's comfort has an analogue in the effective temperature for the vector-borne parasites, which is the temperature range at which they remain infective.

Based on the route of transmission Davey and Wilson ^[74] classify these diseases into 6 groups:

- (a) Diseases due to parasites which have an extra-corporeal developmental phase in their life cycle.
(Examples: the hookworms *Ascaris* and *Enterobius*);
- (b) Diseases due to parasites which pass parts of their life cycle in water in one or more non-mammalian hosts and which have one or more free-living stages.
(Examples: the schistosomes);
- (c) Diseases due to parasites which must complete a stage in their life cycle in a mammalian host other than man.
(Examples: *Taenia saginata* and *Taenia solium*);
- (d) Diseases of animals due to parasites passing from animal to animal which can infect man under certain circumstances.
(Example: Trichiniasis);
- (e) Diseases due to parasites which can be transferred from man to man only by an insect vector. This includes animal reservoirs with transmission of the disease from animal to animal by an insect vector which can also convey the disease to man and thus initiate a human cycle.
(Examples: yellow fever, malaria, epidemic typhus);

- (f) Diseases of animals which can be conveyed to man by a vector. Infection of man is an accident in these cases and a dead end for the parasite.
(Example: bubonic plague);

6.2.1 Non-contagious infections associated with low standards of hygiene

A selection of this group of diseases is listed in the left side of Table 8. In many of these diseases the parasite is water-borne. Transmission results from contamination of water and food with man's excreta or body discharges.

The infections have been divided into 4 groups:

- (a) viral bacterial and protozoal infections resulting from ingestion of water and food contaminated with human faeces or urine;
- (b) worm infections in which transmission follows ingestion of either eggs or larval forms of the parasite;
- (c) worm infections resulting from penetration of the skin by immature stages of the parasite; and
- (d) bacterial diseases due to consumption of infected foodstuffs.

In diseases of group (a) climate affects the survival of the parasites indirectly through the temperature of water and food and directly through solar radiation, to which many viruses and bacteria are non-resistant. For example, cysts of *entamoeba histolytica* are killed by sunlight but in shaded conditions their survival depends on the temperature: at 0 deg C they can survive for several weeks, at 13 deg C to 17 deg C for 2 weeks, but at 34 deg C to 37 deg C they can live for only 1 or 2 days. Hence, amoebiasis can occur with unsanitary conditions in cool and even arctic conditions 81 and high temperatures, as in the tropics, have an adverse effect on the transmission of the disease.

In temperate climates these diseases show seasonal periodicities with the highest incidence during the summer months. The cholera *Vibrio* dies rapidly in pure water and sewage. For its survival it needs water with organic matter and a trace of salt. Even then it survives not longer than 2 weeks depending on the water temperature.

Temperature is of great importance in worm infections by hookworms and schistosomes. Hookworm infections are present between latitudes 35°N and 30°S. Outside these hot, humid areas the disease occurs in mines and other places where temperature and humidity favour the developmental cycle of the worm. The free-living stage in the worm's cycle of development depends on damp soil with decaying vegetation, dark shade and temperatures between 24 deg C and 32 deg C. At higher temperatures the larvae are short-lived while at lower temperatures they can live for several months; they die at temperatures below 0 deg C.

Even more interesting is the climatic distribution of schistosomiasis caused by *Schistosoma haematobium* and *S. mansoni*. The ova of the parasite are excreted in the faeces and urine. Eggs contain miracidia, which survive in hot climates only for about one month. Within this period the eggs must reach water, hatch and then penetrate an aquatic snail host within two days. The multiplication which takes place inside the snail is accelerated by higher and slowed down by lower temperatures. The developed cercaria (larval stage) leaves the snail to go back into the water, where it can live free for 2 to 6 days depending on the temperature. Within this time it must enter a host by penetrating the intact skin of wading or bathing man.

The distribution of the three important forms of schistosomiasis; *Schistosoma haematobium*, *S. mansoni* and *S. japonicum*, are clearly limited by mean temperatures. There are two climatic limits, firstly for the distribution of the vector aquatic snails, and secondly, the climatic limits for the development of the cercaria in the vector. The lower and upper extremes of temperatures for survival of snail embryos and young and adult snails are 10 deg C and 37 deg C, with an optimum temperature of about 24 deg C [82]. In the snail the development of the cercaria takes about 40 days at temperatures around 30 deg C. It can be concluded that with climatic variation snail populations will invade new areas when there are suitable temperatures, and the vector will expand when the suitable warm temperatures remain long enough to favour the development of cercaria (larvae).

Another type of climate related disease is tetanus. The *Clostridium tetani* spores are distributed in the soil. The highest incidence is found in warm countries during the seasons when work is done in the field and where people do not protect their feet. The survival of the spores is temperature dependent. A relationship between temperature and the frequency of isolation of *Cl. tetani* from the soil of certain areas and the level of morbidity from tetanus has been established. The highest rates of morbidity are in the countries near the equator [83].

6.2.2 Insect-borne infections

A list of insect-borne infections is given on the right side of Table 8. Two diseases, epidemic typhus and louse-borne relapsing fever, are transmitted by the human louse *Pediculus humanus*, which inhabits the clothing of the host. The louse lives near the skin in the warm environment of the clothing. The warmer the clothing the better protected it is. Therefore epidemic typhus fever is particularly frequent in cold climates when clothes are seldom changed and body hygiene is poor. In the tropics the disease is absent as long as heavy clothing is not required. The same applies to louse-borne relapsing fever, which occurs in louse-infested populations during cold seasons when people crowd together.

All other diseases listed in Table 8 occur in warm climates where the arthropod vector can exist. Yellow fever is primarily a virus infection of primate species which form the reservoir, while the vector of the arboviruses is the mosquito *Aedes aegypti* [84]. The yellow fever epidemic zone in Africa is shown in Figure 19 [85]. A temperature of 24 deg C or higher and high humidity is required for the development of the virus in the mosquito. Epidemics of the disease during the past remained in areas with a mean annual temperature of 20 deg C or higher between 40°N and 35°S latitude.

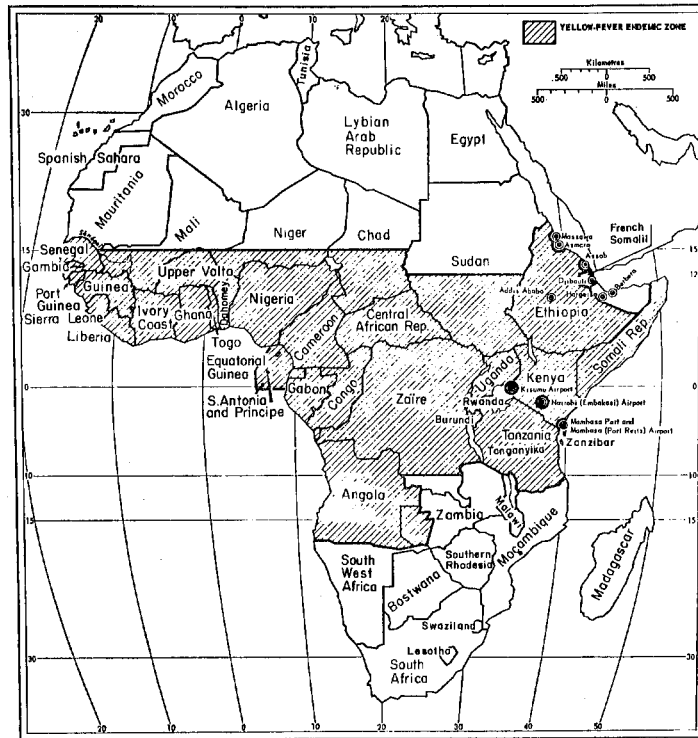


Figure 19. Yellow fever endemic zone in Africa (Source: 84).

Malaria is transmitted by anopheline mosquitos, which live in warm climates and can advance to high latitudes if the climatic conditions are suitable. The distribution of the mosquito is very uneven, varying from one area to another. Receptive areas for malaria exist in climates where the mosquito can live but the parasite cannot develop. Malaria has been reported as far as 65°N and 32°S , and from sea level up to 3 000 m altitude.

The malaria parasite requires a certain minimum temperature for the sporogony inside the mosquito, which is 16 deg C for *Plasmodium vivax* and 18 deg C for *Plasmodium falciparum*. The length of the sporogony is temperature dependent, being shorter at higher and longer at lower temperatures. After the completion of the sporogony a vector mosquito is infective when it bites. This fact has been used with success to estimate the time for the completion of a cycle of sporogony 86.

It is obvious that with climatic changes the potential malaria vector area can alter and expand with warm or collapse with cold climate. In Figure 20 the relationship between malarial conditions and climatic zones are summarized on a hypothetical malaria-infected continent 87. The distribution of seasonal epidemic areas may thus quickly change with major climatic variation.

Filarial infections are widely distributed in the tropics. Man is the definite host of the worm *Wuchereria bancrofti*, which occurs in the New World from Mexico to Lat. 30°S and in the Old World from Lat. 40°N to 30°S . The anopheline

mosquito becomes infected by sucking blood contaminated with embryonic forms which then develop inside the vector to infective larvae. The larvae invade the skin of man while the mosquito is feeding.

The developmental period of *Wuchereria bancrofti* from the embryonic forms to the larvae is temperature dependent: the period is about 10 days at 27 deg C and 40 days at 17 deg C [88]. The optimum ranges for the infectious vector are limited to 21 deg C - 32 deg C and with high humidities of 70 - 100 per cent. The visceral leishmaniasis Kala Azar, common in rural areas along river beds in India and China, is also limited to areas with high humidities, high mean temperatures between 25 deg C and 28 deg C, and a diurnal range of temperature not greater than 11 deg C. It is not found at altitudes above 700 m. The sandfly vector requires water vapour saturated air for its survival.

Human trypanosomiasis in Africa occurs between latitudes 10°N and 25°S. The developmental cycle of the parasite inside the tsetse fly required 18 days at 24 deg C and will be longer when the temperatures are lower [89].

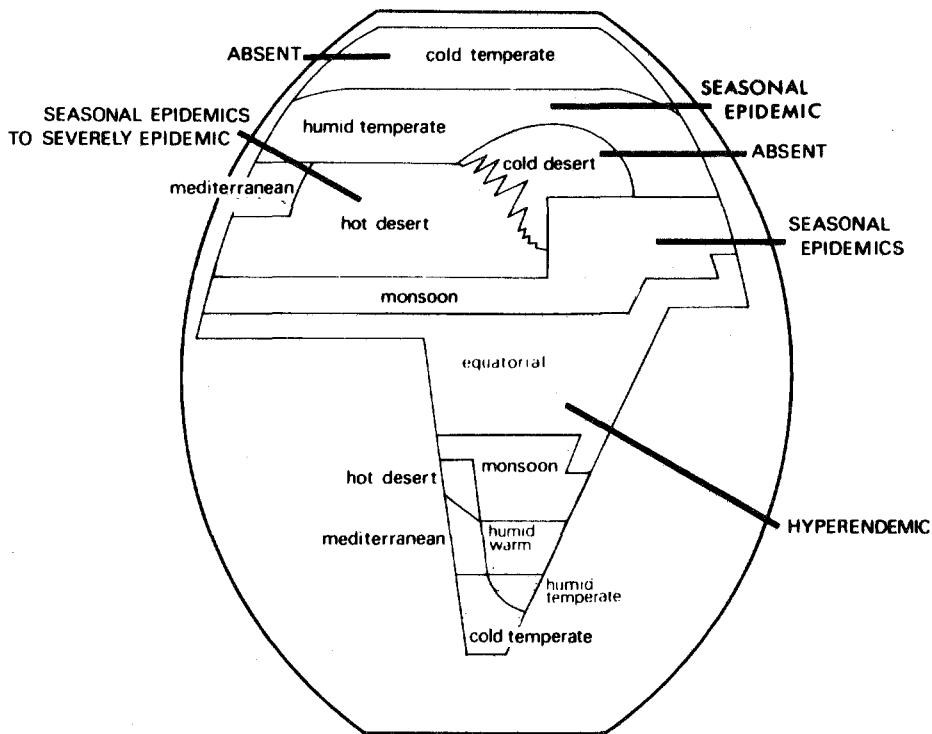


Figure 20. Malarial conditions in the main climatic zones of a hypothetical malarial continent (Source: [87]).

Plague is a disease of rodents. The fleas feed on the rat and suck in the plague bacterium *Yersinia pestis* with the blood. This multiplies inside the flea and in due course is inoculated into a new host during another bite. Infected fleas can also bite man, leading to bubonic plague. Plague is found in the vicinity of rodent vectors, usually in warm climates. In Vietnam the percentage of *Y. pestis* serologically active rats was negatively correlated with rainfall. The number of cases of bubonic plague was at its maximum during the dry season and fell to near zero during the rainy season when the flea population is drastically reduced 90.

To summarize the effects of climate on the occurrence and incidence of communicable diseases:

- (a) In the category of contact infections there are some diseases which are distributed all over the world and others which are limited to warm climates with high or low humidity. The contact diseases are either seasonal, with high morbidity rates either in the winter or in the summer, or in other cases occur at every season. Climate may affect the virulence of the parasite or the resistance of the host or both;
- (b) In the category of non-contagious infections the distribution of the diseases depends on the living conditions of the vector. The vector is highly climate dependent or isothermic. The survival of the parasite inside the vector is equally climate-dependent. Climate thus directly affects the vector, the development and survival of the parasite during the periods outside the homeothermic human host, and (indirectly) the resistance of the host.

7. Climate and public health

7.1 Preventive medicine and health control

Public health comprises all activities that are directly and indirectly concerned with achieving, maintaining and improving health and preventing disease. It depends to a large extent on the climatic conditions, on what particular measures are selected, and to which diseases special attention is paid.

In cold climates attention is focussed on alleviating cold stress with clothing, techniques of heating houses and working rooms, and on contagious diseases, whose incidence increases with crowding during the winter. In hot climates particular importance is attached to the prevention of water- and insect-borne communicable diseases, disease vector control and protection against severe heat stress. Malnutrition is a world-wide public health problem which can cause immuno-deficiency with decreased resistance to communicable diseases. Both malnutrition and communicable diseases show a seasonal pattern of incidence, though the two patterns are not always correlated.

The organization of the health services, the provision of major drugs and vaccines, and the preparation for extreme climatic events such as cold waves, heat waves, drought and tropical storms of course depends on the given climatic variation. The density of health services, the intensity of medical care, the planning of sanitary installations, food control and the design of hospitals depend on the expected climate.

The increasing concern in recent years over the many man-made pollutants in industrialized countries has produced a new awareness of the environment. Air pollutants have indeed become a major environmental hazard 91, 92. Their toxicity is related to their atmospheric concentration, which in turn is closely linked with the local climate. For example, the placing of factories with a high release of pollutants has to take into account the prevailing wind and rainfall.

Proper housing is of major importance in public health. Here climatic conditions play a key role in the requirements for construction, insulation, heating, cooling, and light 40. The development in this field has reached the point at which man has become dependent on artificial climates. Adaptation in a physiological way is no longer the major means of survival in a rigorous climate.

7.2 Climatotherapy

The concept that health can be improved through climate forms the basis of climatotherapy. The therapeutic utilization of particular climatic conditions, either to stimulate the body by enforcing it to adapt to a contrasting climate with a wide variation of conditions or to protect the body in a comfortable climate with little variation, is an old branch of medicine with a long tradition in European countries. In these cases climate serves directly as a resource for better health. For example, winter seasons in Alpine areas are preferred for recreation and sport, as exposure to the cold, dry, clean mountain air in combination with physical exercise has an invigorating effect.

Climates of countries are now classified according to their stimulus effect. Important examples of this are the biometeorological maps in countries like Germany and Switzerland 93. A special application of climatotherapy has developed in the USSR, where climate health resorts have been defined for the preventive treatment of particular groups of diseases, such as cardiovascular disease.

7.3 Disaster and health protection

Particular climatic events such as tornadoes and typhoons can cause great destruction in an area, and this may be followed by epidemic outbreaks of diseases. Knowledge of the frequency of such events in an area is important for decisions on the kind and degree of precautionary measures to be taken in advance. For the prevention of epidemics early distribution of drugs, vaccines, and hygienic measures should be initiated immediately after the storm. Such precautions have proved to be highly successful after tropical storms during which a population may suffer a high death toll from the direct impact of the storm 94.

Such disasters are short lasting events. In long lasting disasters such as drought over a period of several years health precautions for man may be nearly impossible to take, as the area becomes intolerable from heat, lack of water and food. Man will usually be forced out of such areas and search for better climates.

7.4 Biometeorological forecasting

The forecasting of weather, a standard routine in meteorology, can be extended to special applications for the health of man. In biometeorological forecasting the announcement of impending hot and cold conditions are combined with values of the heat stress or of the cooling power (wind chill index) 95. Sudden climatic variations may be combined with a warning for those who are at risk because of disease or high age. Biometeorological forecasting is of value in the case of sudden and temporary climatic variations in order to dampen the surprise effect and to allow for preventive measures. The value of such forecasting over longer periods much be doubted, as man will usually adapt to slowly developing changes, such as from season to season.

8. Importance of future climatic variation for man

8.1 Present developments

During this century man's efforts to improve his well-being and to eradicate the dangers of communicable diseases have achieved remarkable results. Man can feel safer in his natural environment than ever before in history.

The best expression of his achievements are the statistics on mortality showing reductions of mortality rates up to high age groups. Life expectancy has increased in close conjunction with a rapid growth of populations, which is associated with an increasing demand for food and an accelerated exploitation of natural reserves. Simultaneously the conveniences of technology are being introduced to more and more populations in countries of a wide variety of climates and even to primitive communities. The latter had generally developed high levels of cultural adaptation and fitness in extreme climates, and now they have become dependent on technology and foreign sources of energy. The style of living has changed nearly everywhere in modern times, as is expressed in a high mobility in the industrialized countries, permanent settling down of formerly migrating populations in the developing countries, change of agricultural methods and world-wide urbanization with crowding.

The changes in style of living have been achieved at the expense of vast quantities of energy taken from natural resources. The amount of waste products in some places (or even of the globe) is beginning to exceed the buffering capacities of nature. This is the alarming sign that is forcing man to contemplate the usefulness of his activities for the continuing improvement of his comfort and well-being.

8.2 Major climatic variation and its implications for man

It is expected that in the near future as a result of man's activities in his environment the global climate might change with a gradual increase of the mean annual temperature 96. (See overview papers by Mason, Flohn, and Munn and Machta.) This increase would be the result of an up to 8-fold increase of the atmospheric carbon dioxide concentration. The resulting hazards for man's health would be, firstly, the added heat with all its consequences in the ecosystem and, secondly, the larger carbon dioxide concentration. In the human population-climate interaction model the effect of heat would be, as suggested by Figure 21:

- For populations living in the warm intermediate zone the maximum summer temperatures would now lie in the range of maximum strain, close to the limits of tolerance.
- For populations living in the cold intermediate climatic zones there would be more favourable thermal conditions with milder winter seasons.
- For populations in the comfortable climatic zone the cold strain would be less while the heat strain would extend into the former intermediate zone.
- For all those populations living under warm moderate conditions the heat strain would become a major obstacle.

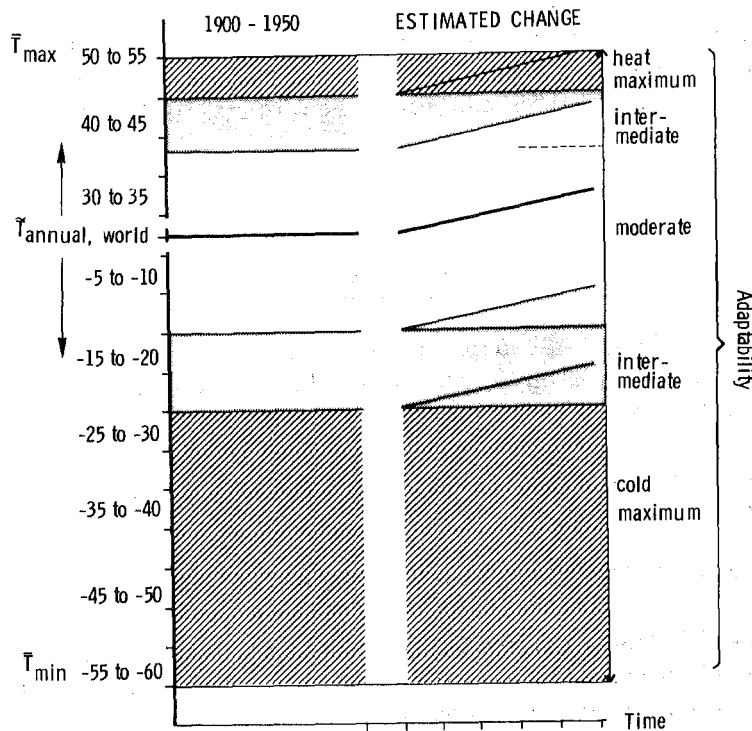


Figure 21. Effect of estimated change of the mean world temperature in the human population-climate interaction diagram (See Figure 4).

The human adaptive responses would be to provide protection against the heat or to migrate to higher latitudes with their cooler, more favourable climatic conditions during the hot season. Since the highest population density already exists in this warm moderate zone, crowding and competition for room could be anticipated with such a migration. The possibilities for man to cope with considerably higher temperatures are small. He will have to look for more suitable climatic conditions where he can develop and can produce the food for his subsistence. In addition to the changing conditions for man the vectors for communicable diseases would follow the climatic changes and introduce diseases into areas that were hitherto disease-free.

The small increase of the carbon dioxide concentration in the air would not be a particular hazard for man. He can adapt to an increase of the atmospheric concentration from the current ambient value of about 0.033 per cent to 0.25 per cent without harm to his respiratory system and metabolism 97.

9. Conclusions

Man is highly adaptable to new or changing circumstances and has the ability to utilize the resources in nature in many ways to further his health and well-being. He has gone far in this drive for comfort and health, with the result that adverse developments are beginning to hit back at him. One day these adverse developments may endanger the fragile balance of man's health control systems, both natural and artificial, with reduction of well-being and reoccurrence of diseases.

One trigger for such an unbalance is to be seen in the prospect of a major climatic variation. Man will have to make every effort to analyse the causes of potentially adverse developments and learn how to mitigate them.

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GLOBAL ASPECTS OF FOOD PRODUCTION

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1. Our agricultural balance sheet and the quest for food self-sufficiency

Food is the first among the hierarchical needs of man. To end the uncertainty in the supply of food, man changed over 10 000 years ago from gathering food to growing food by domesticating plants and animals. This process started two significant developments. First, various forms of energy (collectively termed "cultural energy") were introduced to enable green plants to give stable and higher yields (Figure 1). The relative contributions of the different forms of cultural energy in agricultural production have varied over time and geographic regions. Secondly, from the millions of species recorded in the world flora and fauna, only a few plants and animals were chosen for domestication. Thus, there are now only about 30 plant species whose individual world production exceeds 10 million tonnes per year and six animal species whose production in the form of meat exceeds one million tonnes per year (Figures 2 and 3). Such dependence on a few species for meeting the food needs of the growing global population has increased the vulnerability of food production systems to hazards arising from weather aberrations and pest epidemics. Compounding the problem of man's dependence on a few plant and animal species for his survival is the fact that at present less than ten countries in the world have surplus foodgrains for the export market (Figure 4). A response to this dangerous situation has been the initiation in recent years of steps for developing global and national food security systems.

While the need for introducing an era of accelerated agricultural advance is becoming increasingly urgent, the process of man-made damage to agricultural assets is proceeding unabated. Desertification has been defined as the diminution or destruction of the biological potential of the land ultimately resulting in desert-like conditions, and the entire process was reviewed at a UN Conference held at Nairobi in 1977. Immediate action to combat desertification is essential since, apart from the extreme deserts, about 45 million km² of productive land is threatened, distributed among 100 countries and comprising about 30 per cent of the world's land surface [1]. Lowdermilk [2] in a study of the conquest of the land through 7 000 years, has stressed that while maintaining soil fertility is the duty of the farmer, conserving the physical integrity and production potential of the soil resource is the duty of each nation. In a series of thought-provoking publications, Lester Brown, Eric Eckholm and their associates of the World Watch Institute have drawn attention to the fact that

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apart from the fast depletion of the Earth's non-renewable resources, even the potential for renewable wealth is being destroyed [3, 4]. The impact of man-made activities on the climate, such as the effects of increasing carbon dioxide and of the release of nitrous oxides, freons and other trace chemicals on the ozonosphere is also a matter for serious concern. Above all, the pathway of agricultural advance so far adopted places a heavy reliance on non-renewable forms of energy and if the same pathway is followed in the future, a blind alley could be reached in the matter of improving food production [5].

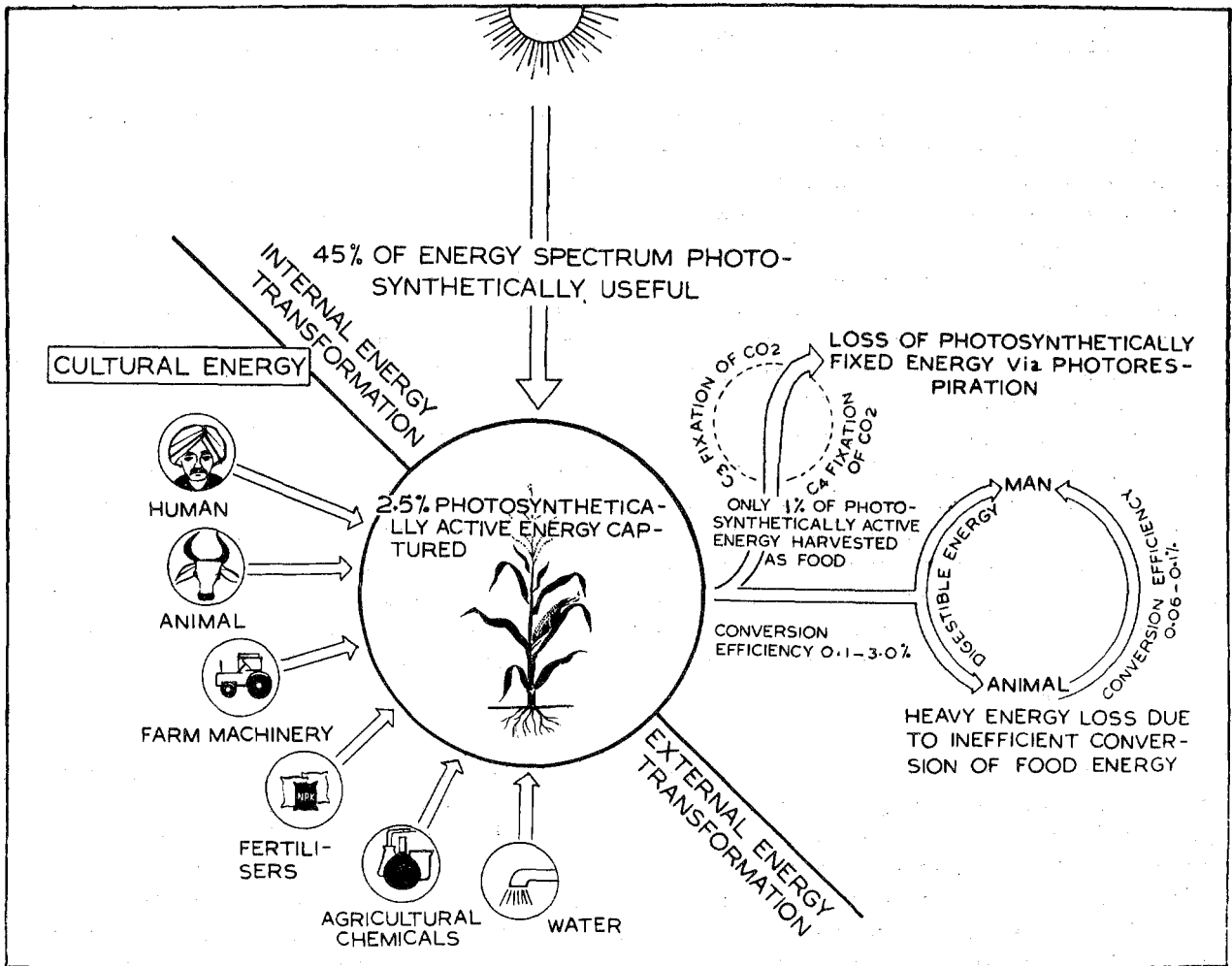


Figure 1. Solar and cultural energy input and output cycle in plants.

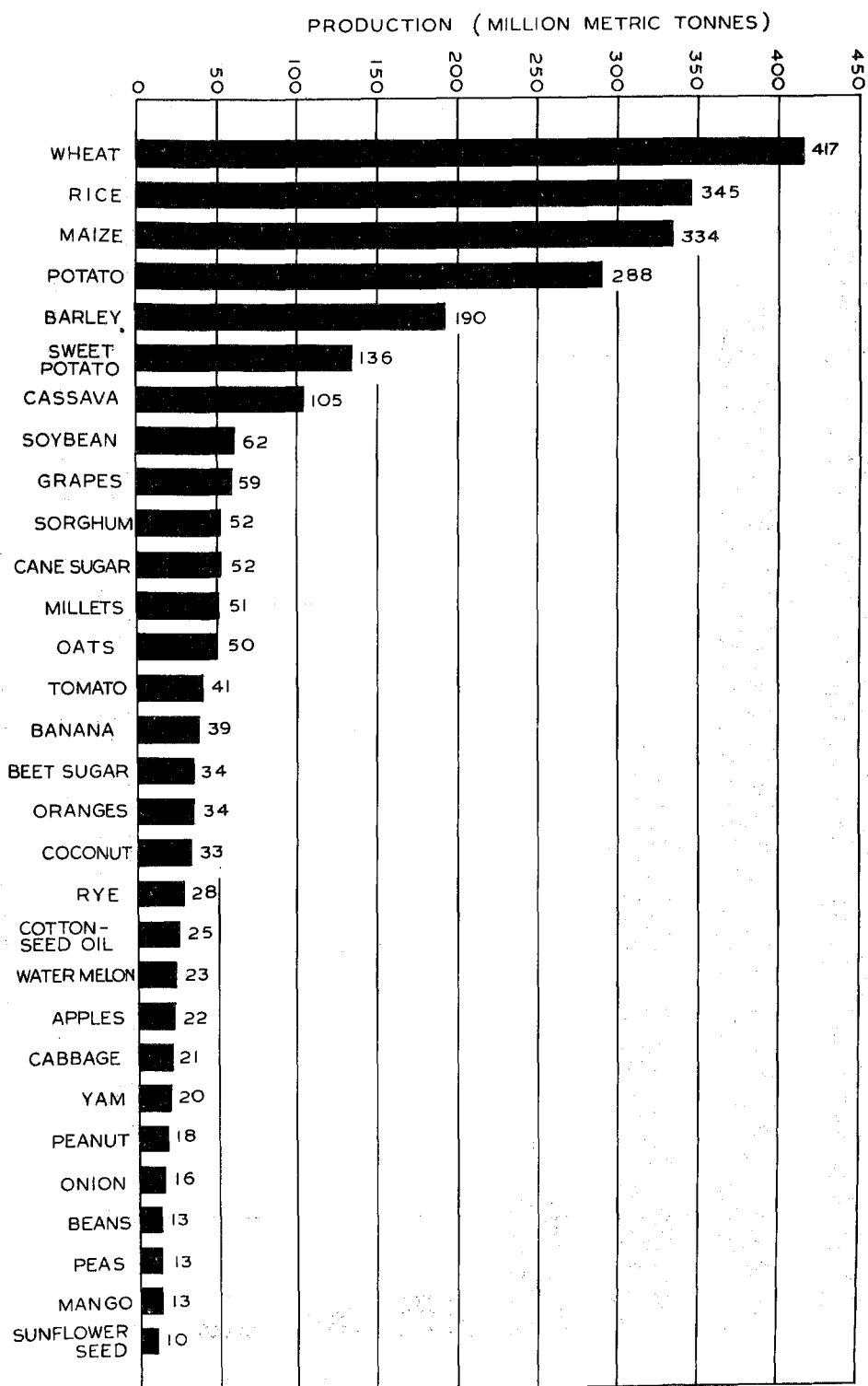


Figure 2. Annual production of the world's major food crops (1976).
(Source: FAO Production Year Book, 1976)

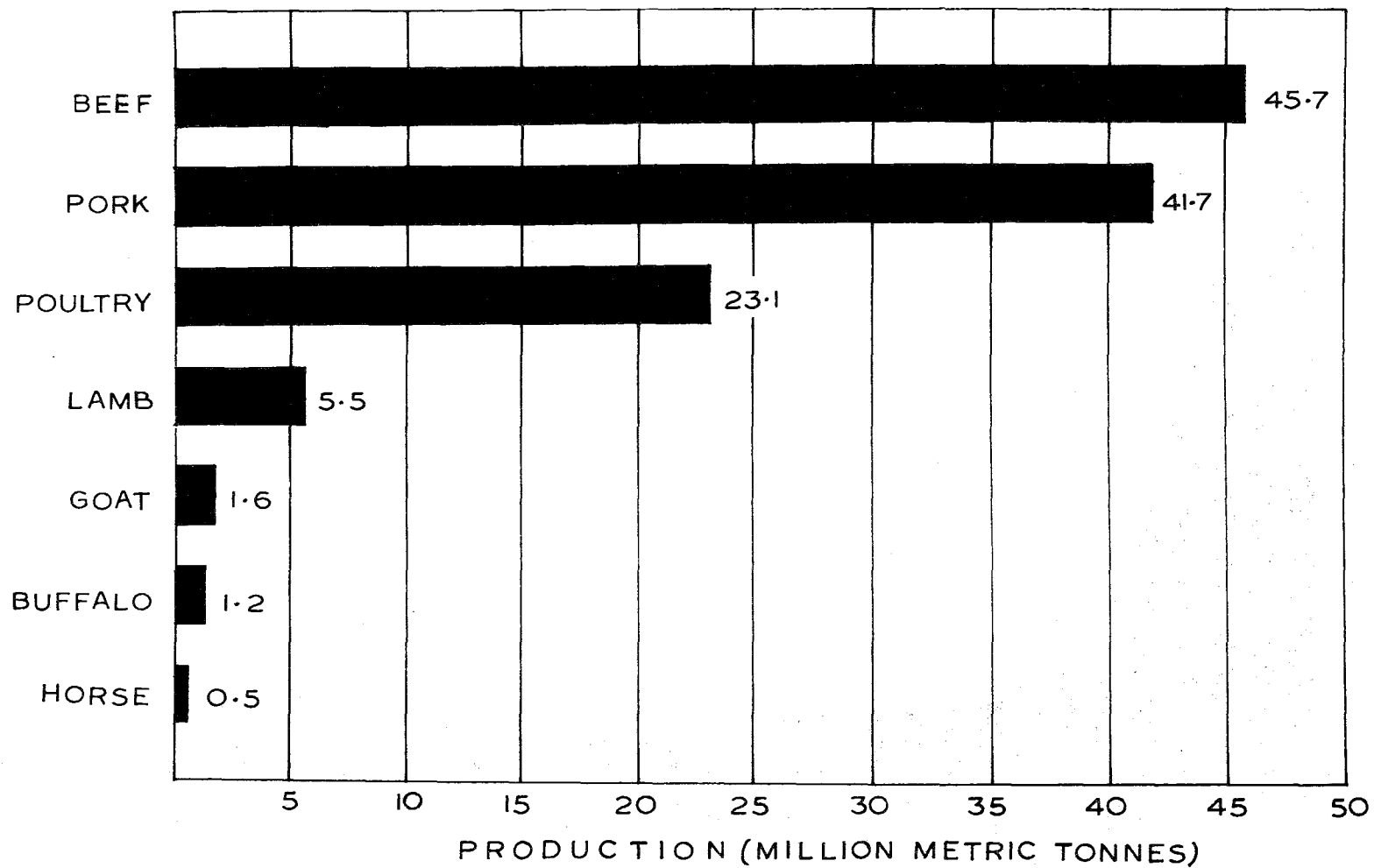


Figure 3 Annual production of the world's major animal products
 (Source: FAO Production Year Book 1976)

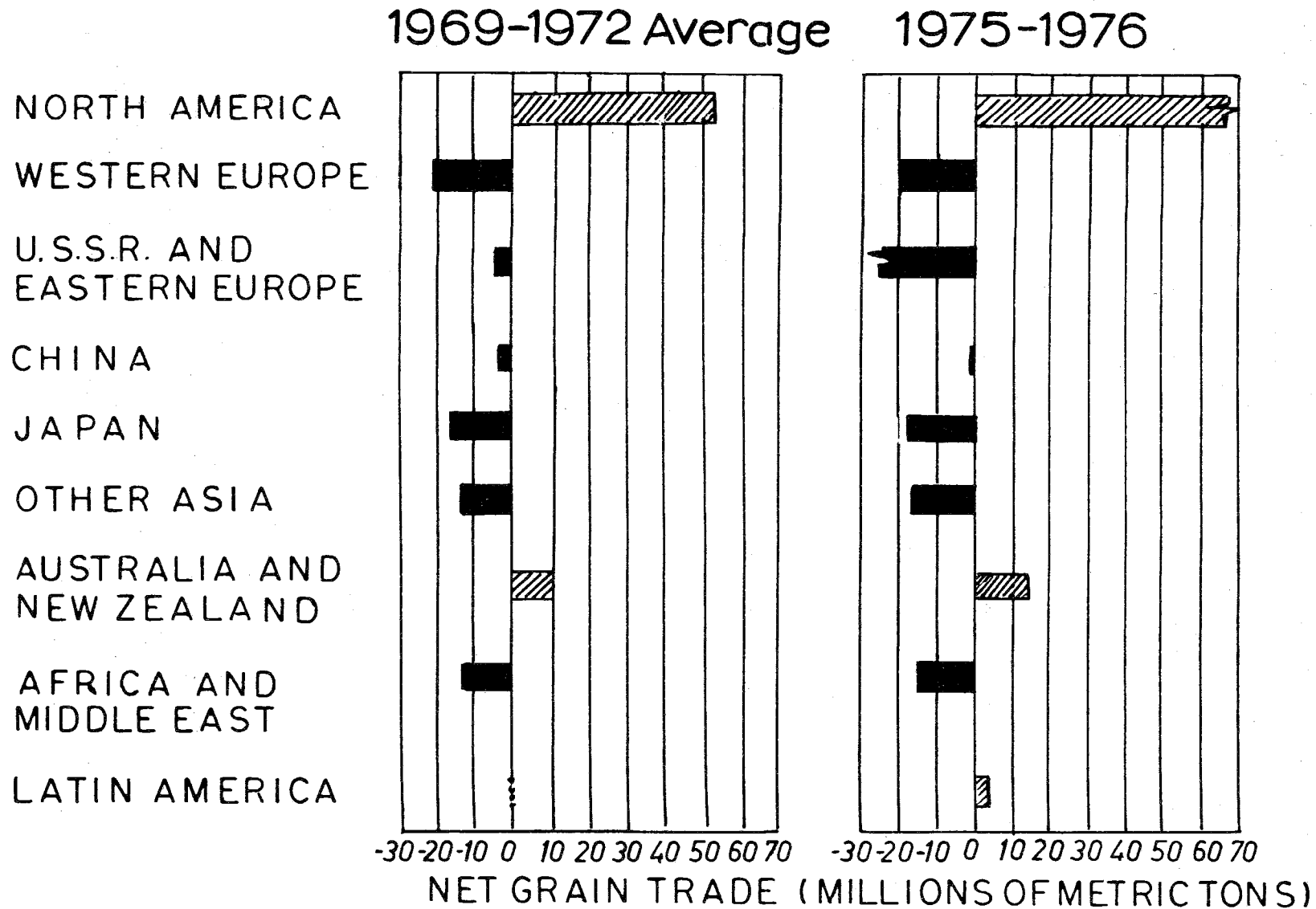


Figure 4 World's increasing dependence on the grain exports of a few countries; U.S.A. and Canada supply most of the grain.
 (Source: U.S. Department of Agriculture 18)

Recent progress in the application of science and technology in the optimum utilization of available soil, water, air, sunlight and biological resources has raised hopes for our agricultural future. Considerable advances have taken place in developing agricultural balance sheets based on an understanding of the production assets and liabilities of each area, and in adapting the architecture and growth rhythm of plants to suit specific agro-meteorological and management conditions. Similarly, integrated animal production systems involving genetic upgrading, better nutrition and health care, and improved processing and marketing have been developed. New vistas of production have also been opened up both in freshwater aquaculture and mariculture, in addition to capture fisheries. In the area of forestry, land management systems involving integrated approaches to silviculture and agriculture (termed "agro-forestry") are emerging. Above all, developments in the area of post-harvest technology are helping to minimize storage losses and to prepare value-added products from all parts of plants and farm animals.

On the basis of a scientific understanding of the global agricultural assets and liabilities, efforts have been made from time to time to measure potential terrestrial and aquatic productivity. Obviously such studies suffer from the limitations imposed by several unpredictable constraints which can retard production. Nevertheless, they are useful for stimulating national and international action since they indicate developmental peaks which countries can try to scale with hope of success. Buringh and his associates [6, 7] have published their estimates of the absolute maximum food production potential of the world and the impact of labour-oriented agriculture on food production. They have used data from soil maps and from recent research on weather and climate. After estimating the area of potential agricultural land in each region of the world with suitable adjustments for soil conditions and water deficiency, they have converted the climatic parameters into a single composite measure called "gross photosynthesis" (GP). They have used appropriate conversion factors to transform GP values into dry matter production and, finally, into grain equivalents. These calculations indicate a theoretical production potential of 49 830 million tonnes of grain equivalents per year. The greatest potential occurs in Asia, followed by South America and Africa (Table 1).

Taking into account the possibilities of irrigation and the limitations of crop production caused by local soil and climatic conditions the absolute maximum production, expressed in grain equivalents of a standard cereal crop, is computed as 49 830 million tonnes per year. Since the average production in recent years has been of the order of 1 300 million tonnes, the postulated production potential is nearly 40 times the present level of production. In other words, we are now exploiting only 2.5 per cent of the absolute maximum potential. It is of course not possible to use all the available land only for growing food crops. The maximum production from the approximately 65 per cent of the cultivated land now used for cereal crop production, could be 32 390 million tonnes or 30 times the present production. Buringh et al. [6] further consider South America and Africa south of the Sahara as the most promising regions for future food production. They consider Australia to be the least promising. Buringh and van Heemst [7] have also stressed the need for greater attention to productivity improvement and increased land use intensity rather than to reclaiming large areas of land which may have adverse ecological consequences.

Table 1

Totals of the production potential of continents and the world

	A	PAL	IPAL	MPDM	PIAL	IPALI	MPDMI	MPGE
S. America	1 780	616.5	333.6	25 224	17.9	340.7	25 710	11 106
Australia	860	225.7	74.2	5 297	5.3	76.1	5 462	2 358
Africa	3 030	761.2	306.5	24 162	19.7	317.5	25 115	10 845
Asia	4 390	1 083.4	433.5	24 966	314.1	581.6	33 058	14 281
N. America	2 420	628.6	320.0	15 443	37.1	337.5	16 374	7 072
Europe	1 050	398.7	233.1	8 289	75.9	247.1	9 653	4 168
Antarctica	1 310	0	0	0	0	0	0	0
Total	14 840	3 714.1	1 700.9	103 381	470.0	1 900.5	115 372	49 830

Legend:

- A Area of a broad soil region (10^6 ha)
- PAL Potential agricultural land (10^6 ha)
- IPAL Imaginary area of PAL with potential production without irrigation (10^6 ha)
- MPDM Maximum production of dry matter without irrigation (10^6 tonnes/year)
- PIAL Potentially irrigable agricultural land (10^6 ha)
- IPALI Imaginary area of PAL with potential production, including irrigation (10^6 ha)
- MPDMI Maximum production of dry matter including irrigation (10^6 tonnes/year)
- MPGE Minimum production of grain equivalents, including irrigation (10^6 tonnes/year)

It is obvious that the figures in Table 1 have to be regarded as highly generalized indicators of the potential for progress. Land will continue to go out of farming as the demand for land for homes, factories and communication increases. More and more soil will be used for brick making. On the other hand, an inexpensive system of solar desalination of water can open up new vistas in production in many coastal and arid areas, including the Australian hinterland. While there are unpredictable trends in the future of agriculture, recent scientific advances, popularly termed as the "Green Revolution" technology, have aroused an awareness of the vast untapped production reservoir existing in most farming systems even at current levels of technology. Hence, it is not surprising that at several international conferences, the view has been expressed that, given a proper blend of political will and professional skill, the problems of hunger and malnutrition can become problems of the past. The World Food Conference (WFC) held in Rome in 1974 even set 1984 as the deadline for achieving the objective of ensuring that no child, woman, or man goes to bed hungry, and that no human being's physical and mental potential is stunted by malnutrition. Nearly 40 per cent of the time set by WFC for accomplishing this goal has elapsed, but

all available statistics show that the number of persons going to bed hungry may in fact be increasing 8, 9. According to recent Food and Agriculture Organization (FAO) statistics 9, a calorie gap of 230 000 million calories per day or the energy equivalent of 37 million tonnes of wheat per year exists in the most seriously affected (MSA) countries from the point of view of minimum nutritional requirements. It would hence be useful to analyse the current world food situation, trends in demand and supply, factors responsible for instability in production and the steps needed to achieve the WFC goal.

2. The current world food situation

Several international and national agencies, particularly the Food and Agriculture Organization of the United Nations, the International Food Policy Research Institute (IFPRI) and the US Department of Agriculture have been issuing from time to time reports on the world food situation 9, 10, 11. Based on these documents, the situation on the food production front can be summarized as follows.

World production of cereal grains (about 1 200 million tonnes) needs to expand by about 25 million tonnes per year to meet rising demand, since population increases by about 75 million annually, and one tonne of grain feeds on an average three people. In 1972, however - for the first time in twenty years - world output actually declined by about 33 million tonnes because of adverse weather. (Since 1972, output has fluctuated - rising in 1973, declining in 1974 and rising again from 1975 onwards 7.)

World food demand is expected to grow at a rate of about 2.4 per cent a year until 1985, while the production growth rate is expected to average about 2.5 per cent a year. In the developing countries, however, the anticipated increase in demand is 3.6 per cent. These projections are based on past trends and exclude serious crop failure, major changes in government policies or relative prices and qualitative improvement in diets.

Since demand in the developing countries continues to grow faster than production, the deficit of cereals is expected to increase from an average of 16 million tonnes per year from 1969 through 1972 to around 85 million tonnes per year by 1985. This prospect is made all the more awesome by the fact that the average cost per tonne of cereals has more than doubled in the last few years.

In 1972, even before the oil-price rise and the related fertilizer-price increase, world cereal prices rose steeply. In spite of good 1973 harvests, prices reached even higher levels by early 1974. Although these increases were offset to some extent by greater earnings from exports, the profits were unevenly shared; the countries that suffered the most gained the least.

Before World War II, Asia, Africa and Latin America, as regions, were net exporters of foodgrains. During the period 1934-38, an average of 12 million tonnes of cereal grains used to be exported from these regions. However, largely due to a rapid increase in population size, these regions became importers of food. The annual imports were of the order of 5 million tonnes during 1948-52. This figure became 19 million tonnes in 1960, 36 million tonnes in 1966, 47 million tonnes in 1973 and 60 million tonnes in 1975.

As a result of these developments, increased numbers of people, now totalling an estimated 25 to 30 per cent of the population in Africa and South Asia, suffer from malnutrition or undernutrition. Malnutrition appears to affect around 460 million people in the developing world, and this is a conservative estimate. Even in countries with a substantial grain reserve, like India, inadequate purchasing power arising from unemployment and under-employment results in undernutrition among the economically handicapped sections of the community. In several MSA countries, emergency situations arising from national calamities like flood and drought aggravate problems of unemployment and undulations in production. Hence, direct State intervention in organizing food and health relief operations often becomes necessary. Guidelines are now available for organizing such relief measures effectively 12.

3. The challenge for the future

As for the future, the following projections were made by the International Food Policy Research Institute (IFPRI) in December, 1977 10.

"Longer term food prospects in food deficit countries with developing market economies remain unfavourable, despite good crops during the last two years. Under the conditions assumed in this study, production of staple food crops in these countries would fall short of meeting demand in 1990 by 120-145 million tonnes. This is over three times the shortfall over 37 million tonnes in the relatively good production year.

The core of the food problem is the low income food deficit countries in which the per capita GNP in 1973 was less than \$300. These countries have almost two-thirds of the total population of the developing market economies (DMEs). Their food deficit is projected to rise from 12 million tonnes in 1975 to 70-85 million by 1990. Just to maintain consumption at the 1975 per capita level would require 35 million tonnes more than the projected production."

The most recent comprehensive survey on the world food problem is by FAO 9. The Survey clearly brings out that there is a widening gap in per capita food production between the developed and developing countries (Figure 5). Data on the average annual rates of growth of food production in relation to population are given in Table 2.

In its agricultural commodity projections for 1970-1980, FAO had concluded that world production of cereals is likely to exceed projected demand in 1980 by a margin of 62 million tonnes. However, the study also concluded that in 1980 there could be no substantial reduction in the absolute numbers of people suffering from undernutrition 9. The projections of USDA 11 also suggest that the world is capable of producing enough grain at reasonable prices to meet the demands of a largely cereal diet in the developing world. Why should food grain surplus and hunger co-exist? This question is most relevant to the most seriously affected (MSA) countries, which account for about 50 per cent of the total population of the developing world, and show a steady decline of per capita availability of food and the dependence by a majority of the population on agriculture for employment and income.

The Fourth World Food Survey ^[9] indicates that in MSA countries there is need for a minimum growth rate of 4 per cent per annum in food production between 1974 and 1990, in order to provide 2 500 calories per head per day. This would call for a doubling of current growth rates in food output in MSA countries.

Table 2

Percentage annual growth of population and food production

Region	<u>Population</u>		<u>Food Production</u>			
	1961-70	1971-76	<u>Total</u>		<u>Per capita</u>	
			1961-70	1970-76	1961-70	1970-76
All developed countries	1.0	0.9	2.4	2.3	1.4	1.4
All developing countries	2.3	2.3	3.1	2.7	0.7	0.3
World	1.9	1.9	2.7	2.4	0.8	0.5

4. Aquatic production

Before considering how this challenge can be met, it would be useful to consider the trends in aquatic productivity, since with growing pressure of population on land, the fisherman and the sea will have to receive as much attention as the farmer and the soil. This will be particularly true for countries with a long coastline, since with the declaration of a 200 mile "Exclusive Economic Zone", the ocean surface available to them for scientific management and use may be substantial. For example, the area of the ocean space available to India under the "Exclusive Economic Zone" principle would be about 2 million km² as compared to the total land area of 3.28 million km².

According to the recent FAO projections issued in June, 1978 ^[13], the current position with regard to world fisheries production and consumption is as follows.

Since 1971 the rate of growth of world fisheries production has declined sharply. In the fifties it grew at almost 7 per cent per annum, in the sixties at a little under 6 per cent but in the seventies the rate of increase has fallen to less than 1 per cent. The principal cause of this decline has been the collapse of a number of important fisheries exploited largely for the production of fish meal and oil. Among these, the most important has been the southeast Pacific anchoveta fishery which in 1976 yielded some 4 million tonnes compared with 12 million tonnes in 1970, but other fisheries, e.g., the Atlanto-Scandian herring, of less absolute size have shown similar proportional declines. Total landings of fish for reduction delivered to fishmeal plants which reached a peak of 26.5 million tonnes in 1970 had by 1973 declined to 18.5 million tonnes and, although production has since recovered, it is well short of the 1970 level.

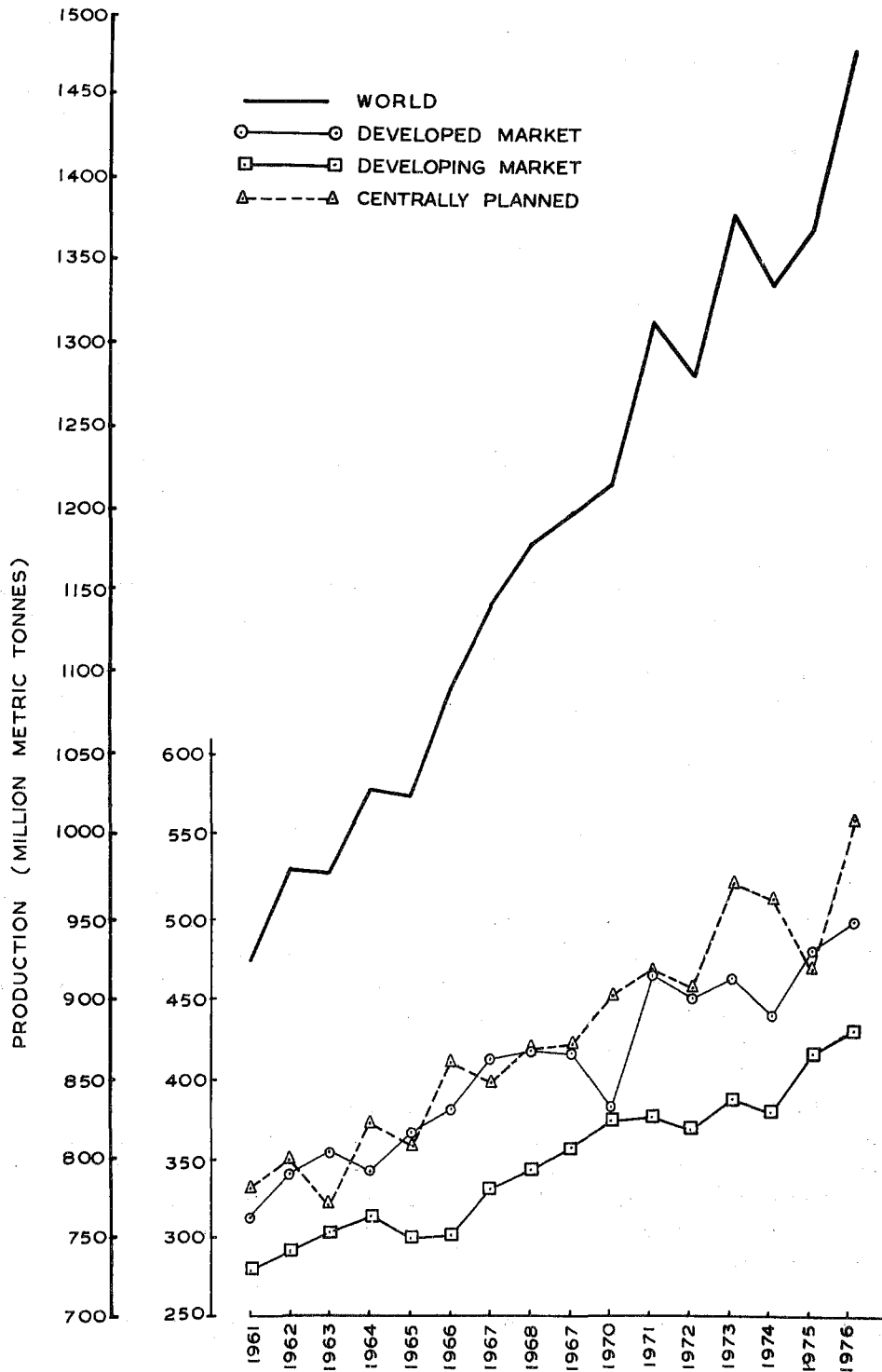


Figure 5. Food production trends in developed, developing and centrally planned countries. Source: FAO Production Year Books 1972 to 1976.

Landings of food fish destined for direct human consumption have by contrast continued to increase throughout the seventies, but even here the rate of growth at 2.5 per cent per annum has declined from that achieved in the 1960s. The basic cause of this decline, as in the case of the reduction fisheries, is the growing number of stocks becoming fully exploited and the rapidly shrinking opportunities for the diversion of fishing effort to new species or areas. Thus in many developed countries where technological innovation led early to the heavy exploitation of stocks in adjacent waters (e.g., the North Atlantic) there has been little or no increase in food fish production. Growth has come mainly from Japan and the U.S.S.R. (and other eastern European countries) which have increasingly had to rely on long-distance operations. There has also been steady growth in the developing countries, both from long-distance operations and from local resources often exploited by less intensive methods than employed in northern temperate waters.

Much of the effort in the developing countries has, however, been directed toward export fisheries (tuna, shrimp, etc.) and thus supplies available for direct human consumption in these countries have risen less rapidly than production. In the sixties per capita intake in this group of countries as a whole rose by about half a kilogramme and in the first half of the seventies by a further 200 grammes. In the developed countries there has been a marked difference in the experience of eastern Europe and the U.S.S.R. where per capita consumption rose by some 9 kg in the sixties and a further 3 kg in the first half of the seventies, and the countries of western Europe and North America where consumption has stagnated. Of the other developed countries, only in Japan and Spain has there been any significant increase in per capita fish consumption in the past decade.

In contrast to the actual fish harvests, theoretical estimates of potential productivity at various trophic levels reveal a vast untapped production reservoir. For example, the total fish biomass for the world as a whole has been put at 640×10^6 tonnes, assuming that the harvest is taken at the second stage of carnivores with a 15 per cent ecological efficiency factor. The krill resources alone have been estimated to range between 750 and 1 350 million tonnes with an annual harvestable yield of 100 to 150 million tonnes from the Southern Ocean. Out of this, only about 20 000 tonnes are being harvested.

In addition to the potential for capturing additional quantities of fish through improved technology, there is vast scope for culture fisheries both in inland and coastal waters. Modern fish farming techniques are as exciting as recent developments in crop or animal husbandry. By appropriate integrated strategies of capture fisheries, the availability of fish products both for human and animal consumption can be increased considerably.

5. Impact of the plant-animal-man food chain on world food needs

According to FAO statistics [9], animal products contributed about one-third of the per capita calorie supply and more than half of the protein in the diet of the population of developed countries. The share of animal products in the diet of the consumers of developed countries is still rising (Table 3).

Table 3

Percent contribution of various food groups in daily calorie supply,
per capita basis (per cent)

Regions	<u>Vegetable products</u>				<u>Animal products</u>			
	<u>Cereals</u>		<u>Total</u>		<u>Milk</u>		<u>Total</u>	
	1961-63	1972-74	1961-63	1972-74	1961-63	1972-74	1961-63	1972-74
<u>Developing Market Economies</u>								
MSA countries	64.6	65.8	93.9	93.8	3.1	3.2	6.1	6.2
Non-MSA countries	50.5	51.6	89.6	89.7	2.9	2.8	10.4	10.3
<u>Developed countries</u>								
<u>Developed Market Economies</u>								
World	50.2	49.4	82.7	82.6	5.0	4.7	17.3	17.4

Source: FAO The Fourth Food Survey - 1977. Note: MSA = most seriously affected.

The plant-animal-food chain is also important among developing countries in Latin America, the Near East and parts of Africa. In contrast, this chain provided only about 6 per cent of total calories and 14 per cent of protein in the MSA countries. This is to be expected since grain consumed directly by people provides two to five times the calories it would if converted to livestock products and then consumed. In countries with high average meat consumption as in U.S.S.R. nearly 1 tonne of grain may be needed to feed one individual in a year in contrast to the global average of 1 tonne per three persons. In India, nearly 6 persons survive on one tonne of grain. Thus, although the plant-animal-man food chain may have some nutritional advantages (and also some disadvantages arising from over-consumption of fats), it is expensive in terms of total grain and energy needs (Figure 1).

Due to a positive correlation between affluence and the consumption of animal products, about 30 per cent of the world population in developed countries uses about two-thirds of the world grain supply. About 60 per cent of this quantity is used as livestock feed. In 1976, about 480 million tonnes of grains were fed to livestock. This quantity is more than the total food grain consumption by the human population of China and India taken together. In fact, the total amount of cereals used as human food in all developing countries was only 37 million tonnes more than the amount of 480 million tonnes of cereals used as animal feed in the world.

6. Trends in demand for food

The demand for food is influenced by factors such as population and income growth, the level and distribution of income and the proportion of income spent on food.

6.1 Population growth

The total world population was about 3.8 billion in 1973. The annual increase, at present, is about 70 million people, nearly double what it was in 1950.

Food demand as well as economic development are affected by the striking differences in the rate of population growth between the rich and poor nations. The population growth in the developed countries has declined to about 0.9 per cent annually. In contrast the population in the less developed economies is expanding at a rate of more than 2.5 per cent. At present, 70 per cent of the world's population live in the developing countries. These countries account for 86 per cent of the increase in world population. In 1960, the developing countries had about twice the population of the developed countries but because of rapid population growth they will have three times as much by 1985. The rate of growth in population will hence be a major determinant in finding an equilibrium between demand-supply equations in food output.

6.2 Income and demand for food

As income rises, the consumer buys more food, but a smaller proportion of income is spent on food. However, income is rising throughout the world at different rates. As a result of population and income growth, world demand for food grains increased at a little less than the rate of expansion in food production for several years prior to 1972. In rich nations, the growth in demand was due, mainly, to the growth in incomes, and the demand for grain was relatively higher because of low prices during the latter part of the 1960s. A rapid growth in income also generated demand for livestock products particularly in developed countries. In the developing countries, population expansion is the major factor for increasing demand for grain.

Income elasticities expressed as the ratio of the percentage increase in consumption of a given food to a percentage change in income for a few selected countries and the world as a whole are given in Table 4.

Table 4

Income elasticities for selected food

Food	India	Brazil	Japan	US	World
Wheat	.50	.40	.10	-.30	-.24
Rice	.40	.20	-.10	.20	.23
Maize	-.10	-.30	-.50	-.10	.10
Meat	1.17	.48	.79	.24	.32
Total Food	.43	.19	.13	-.01	.10

A smaller proportion of the food budget is allocated to cereals by the consumers of developed nations. The income elasticities of livestock products are relatively higher. This is an indication of the growing indirect consumption of grains to which a reference has been made earlier.

The future demand for food for a large part of the world's population will continue to be a problem of grain availability and its price. The likely world demand for cereals as suggested by Aziz is given in Table 5.

Table 5

World demand for cereals 1970 actuals, 1980 and 2000 projected

	1970			1980			2000 (metric tonnes)		
	Food	Feed	Total*	Food	Feed	Total*	Food	Feed	Total*
Wheat	215.7	69.4	332.5	253.2	93.7	403.7	368.8	152.6	601.3
Coarse Grain	142.8	384.4	566.0	172.3	465.8	733.7	252.8	780.1	1186.6
Rice	270.0	4.6	310.0	346.7	8.2	400.1	543.5	20.6	633.0

* Total includes other uses also.

6.3 Availability of food

The Fourth World Food Survey of the Food and Agriculture Organization observed that the average quantity of calories available on a per capita basis for the years 1961-63 through 1972-74 in the developed countries was high throughout the period. This was 23 to 31 per cent more than the actual requirements. For the developing countries, it had also risen, but from a lower base, and was inadequate in relation to requirements. However, the trends in these countries were dissimilar. The increase in the availability was only marginal in the 1970s in the Near East and Latin America and a decline occurred in Africa and the Far East 9. The situation is unfavourable in the MSA countries where the calorie supplies on a per person basis were reduced in 1970-74 to a level of 2 030 from 2 040 in 1961-63. On the other hand in the non-MSA developing countries there was an increase of 7 per cent 9.

The World Food Survey further indicates that the availability of protein witnessed a relatively larger gap in the developed and developing countries. In the developing regions as a whole, the per capita supply of protein was only 58 per cent of that in the developed world. Moreover, this proportion remained more or less unchanged during the entire period. The lowest level was noted for the Far East and the highest in Latin America and the Near East.

The supply of protein in MSA countries was 11 per cent less than that in non-MSA countries in 1972-74. The developed nations had greater availability of proteins of animal origin, while the level of plant protein was similar in both groups of

nations. However, the proportion of animal protein in the case of developed countries showed a rising trend whereas in the case of poor countries it remained stationary at one fifth (Table 6). In the case of availability of fats, it was reported that the developed countries had more than three times more fat compared to developing countries in 1961-63. This ratio rose to three and half times in 1972-74.

Table 6

Per capita daily food supply in terms of protein (Grams)

Region	<u>Total Protein</u>		<u>Animal Protein</u>	
	1961-63	1972-74	1961-63	1972-74
Developed Countries	90	95	48	56
Developing Countries	53	57	11	12
World	65	69	22	24
MSA Countries	53	51	7	7

6.4 Composition of food supplies on a per capita basis

Food supplies in the developing world, in general, are inadequate in relation to energy requirements. The composition of diet also reflects the lack of diversity. According to the Fourth World Food Survey of the FAO, cereals contributed about half of the total calorie intake on a per capita basis in the world. During 1961-63, an average person in the developed countries had 36 per cent cereals in his diet. On the other hand, cereals provided about two thirds of the calories in the MSA developing countries.

The Food Survey further indicates that "maximum reliance on cereals as a source of dietary energy was in the Far East and the Near East regions; and the minimum in Latin America. During the period under review, the importance of cereals as a major component of diet was steadily declining in the developed countries partly due to the growing share of meat. On the other hand, dependence in the Far East on the cereals as a source of calorie supplies rose slightly between 1961-63 and 1972-74, mainly due to shrinkage in the availability of pulses, nuts and seeds" [9].

It is now widely accepted that in areas where a cereal is a staple food, under-nutrition may be the primary cause of malnutrition [14]. In contrast, in areas where cassava or sweet potato is the staple diet, inadequacy of proteins in the diet may be a serious problem. It is in such areas that Kwashiorkor in children is widely noticed. In cereal based diets, Marasmus arising from calorie deprivation is relatively more common.

7. Achieving equality in distribution

As pointed out earlier, there are wide disparities in the consumption of both plant and animal products in the developed and developing countries. Also, there are considerable differences in the quality and quantity of food consumed within each developing country, based on the extent of prevalence of economic and ethnic disparities. Inadequate purchasing power rather than non-availability of food in the market may be the primary cause of undernutrition even in many MSA countries. Hence, reducing the degree of inequality in food distribution should receive as much attention as accelerating food production. An important requirement in this context is a strategy for generating more opportunities for gainful employment in rural areas.

7.1 Unemployment as a key factor in under- and malnutrition

Economists estimate that for every 1 per cent growth in the labour force, a 3 per cent rate of economic growth is required to generate jobs. With current technology, countries experiencing a 3 per cent rate of population growth therefore require a 9 per cent rate of economic growth just to maintain employment at its current level. A much higher growth rate will be needed to achieve full employment. Unfortunately, economic growth rates have been falling during the seventies ^{15/}. Since agriculture is the major source of employment in many developing countries, agricultural policies will have to aim at creating more jobs and income in addition to more food.

Looking at the developing nations as a whole, the International Labour Organization (ILO) estimates that 24.7 per cent of the total labour force was either unemployed or underemployed in 1970. The comparable figure for 1980 is expected to rise to 29.5 per cent. Yet, the labour force in the less developed nations is projected by the ILO to expand by 91 per cent between 1970 and the end of the century, nearly doubling within the span of a single generation. The labour force in the more developed regions is expected to increase by only 33 per cent during this period (Table 7).

Table 7

Projected growth in world labour force, 1970-2000*

	1970 (m i l l i o n s)	2000	Additional jobs required	Change 1970-2000 (per cent)
More developed nations	488	649	161	+33
Less developed nations	1 011	1 933	922	+91

* Source: ILO (cited in reference ^{15/})

Further aggravating the problem, the number of persons requiring non-agricultural employment in developing economies will increase from 342 million in 1970 to a projected 1 091 million in the year 2000, a staggering increase of 219 per cent in one generation. Few, if any, developing countries have the kind of investment capital needed to generate new jobs at such a fast pace. Thus, a massive effort is needed to generate jobs both in the agricultural and non-agricultural sectors. The vast dimensions of this problem and the lack of adequate resources for the effective utilization of the available manpower necessitate the development of employment generation policies based on the scientific utilization of local resources. Without such an approach it will be difficult to initiate self-replicating and self-propelling systems of rural development.

Depending on the extent and quality of unemployment, technologies appropriate to the socio-economic conditions of each country should be developed and disseminated. A good example of appropriate technology under conditions of rural unemployment and underemployment is the development of hybrid cotton in India based on seed produced by hand emasculation and pollination. A one-hectare hybrid seed production unit in cotton may provide jobs for 80 women for 100 days. Creation of opportunities for gainful employment of women is particularly important since rural women tend to remain underpaid or unpaid for most of the jobs they currently perform.

7.2 Impact analysis

In view of the linkages among poverty, unemployment and hunger, there is need for subjecting all developmental projects to impact analyses from the ecological, economic, employment and nutritional viewpoints. The criteria used for measuring the likely social impact of a new technology must include employment. It is also essential that the impact analysis is designed to measure the implications of new projects on the economic and nutritional well-being of women and children, if the goal of ensuring their physical and mental potential is not to be frustrated by malnutrition. An impact analysis of this kind can help to correct distortions in priorities which may arise if human needs are overlooked. For example, supplies of fish available for direct human consumption in several MSA countries have remained practically stagnant, while exports of fish products have grown.

8. Risk and uncertainty in food production

The three major factors which influence variations in yield and food production are weather, pest epidemics and public policies.

8.1 Impact of weather on terrestrial and aquatic productivity

According to an analysis of the U.S. Department of Agriculture [11], there is a positive correlation between the effects of weather in one place and those in another. An analysis of yield trends and variations in 25 regions covering the world's major grain producing areas indicates that when grain yields decline because of adverse weather in one part of the world, the chances are better than even that they will be lower in many other parts of the world too. Unfavourable weather conditions played a dominant role in causing major declines in food production in 1964-66

and 1972-74. Conversely, good weather tends to be experienced also at the same time in many parts of the world. However, the analysis did not reveal the existence of weather cycles or trends during 1950 to 1973.

8.2 Variation in yield caused by weather factors

An analysis of variation in grain yield in several parts of the world during 1950-73, showed that the weather in one year out of three could be expected to produce a deviation greater than 21 million tonnes from trend production in the 25 regions studied (Table 8).

Table 8

Changes in grain production due to weather in
25 major world grain producing regions
(data from reference 11/)

Grain	Without covariation ⁽¹⁾ (million metric tons)	With covariation ⁽²⁾	Per cent difference
Wheat	11.59	13.28	+15
Rice	4.58	4.81	+5
Corn	5.68	6.24	+10
Barley	5.13	5.42	+6
Oats	1.95	2.23	+14
Sorghum-millet	2.06	2.23	+8
Rye	0.91	1.03	+13
Coarse grains (incl. rye)	8.22	10.04	+22
All grains (incl. rice)	14.74	21.08	+43

(1) Assumes that yield fluctuations are not related

(2) Includes interrelation between yield fluctuations

There has been considerable interest in recent years on climate in relation to production, in view of reported changes in climatic trends. Several scenarios have been constructed. A recent study organized by the National Defense University of the United States, for example, considered five different possibilities including large global cooling, moderate global warming, large global warming 16/.

The derived climate scenarios manifest a broad range of perceptions about possible temperature trends to the end of this century, but suggest as most likely a climate resembling the average for the past 30 years. Collectively, the respondents tended to anticipate a slight global warming rather than a cooling. More specifically, their assessments pointed towards only one chance in five that changes in average global temperatures will fall outside the range of -0.3 deg C to $+0.6$ deg C, although any temperature change was generally perceived as being amplified in the higher latitudes of both hemispheres. The respondents also gave fairly strong credence to a 20- to 22-year cycle of drought in the High Plains of the United States but did not agree on its causes.

The question of temperature change was also discussed in detail at a Conference held in Bellagio in Italy in June, 1975. The following conclusions were drawn 17.

- (a) Climate variability, region by region and from year to year in particular regions, is and will continue to be great, resulting in substantial variability in crop yields in the face of increasing global food needs and short supplies.
- (b) There is some cause to believe, although it is far from certain, that climatic variability in the remaining years of this century will be even greater than during the 1940-1970 period.

The implications of the undulations in food production caused by climate have been examined at several international conferences. More recently, the climate-food output relationships have assumed importance in relation to the grain reserves necessary for building global and national security systems 18, 19. Walters 18 has stressed the need for utilizing the surplus wheat of some 40 to 50 million tonnes available during 1977-78 for building a grain reserve, either an insurance reserve of 20 to 30 million tonnes or a major stabilization reserve of 50 to 60 million tonnes. While the building of such grain reserves at the global, regional and national levels is exceedingly important for off-setting the shortages caused by weather aberrations, it is also essential that steps are taken to insulate agricultural fortunes from the vagaries of climate to the extent possible. The following are some of the major steps needed for this purpose.

8.3 Expanding the area under assured irrigation

Wherever possible, steps for increasing the area under assured irrigation should receive the highest priority. This is particularly important in the tropics and sub-tropics where (a) the rainfall distribution is often skewed, (b) the evapotranspiration rates may be high throughout the year and (c) the period of maximum insolation often coincides with the period of minimum precipitation. Without assured water supply, fertilizer application becomes risky and yields tend to remain low. In rice, which is the second major crop of the world, there is in Asia a strong positive correlation between the proportion of area under irrigation and average yield (Figure 6). In India, studies by the India Meteorological Department reveal that variation in climate resulting in drought, floods, high evapotranspiration, etc., may account for more than half the variation in the yield of crops. Also it is not just total rainfall but rainfall during critical stages in the growth of the plant such as

the grain development phase that influences the ultimate yield. The stabilizing influence of irrigation was brought out by Chowdhury and Rao ²⁰, who studied the effect of climate change on wheat yield in the States of Punjab and Haryana of India over a 50-year period (1911 to 1960). Rainfall and mean daily temperature from December to February were examined in relation to the mean yield of wheat. There was a striking correspondence between rainfall and yield till about 1940. After 1940, the rainfall showed a falling trend but the wheat yield went up. This was attributed to the increase in the area under irrigation (Figure 7).

CORRELATION OF INTENSIFICATION OF FARMING AND YIELD OF RICE

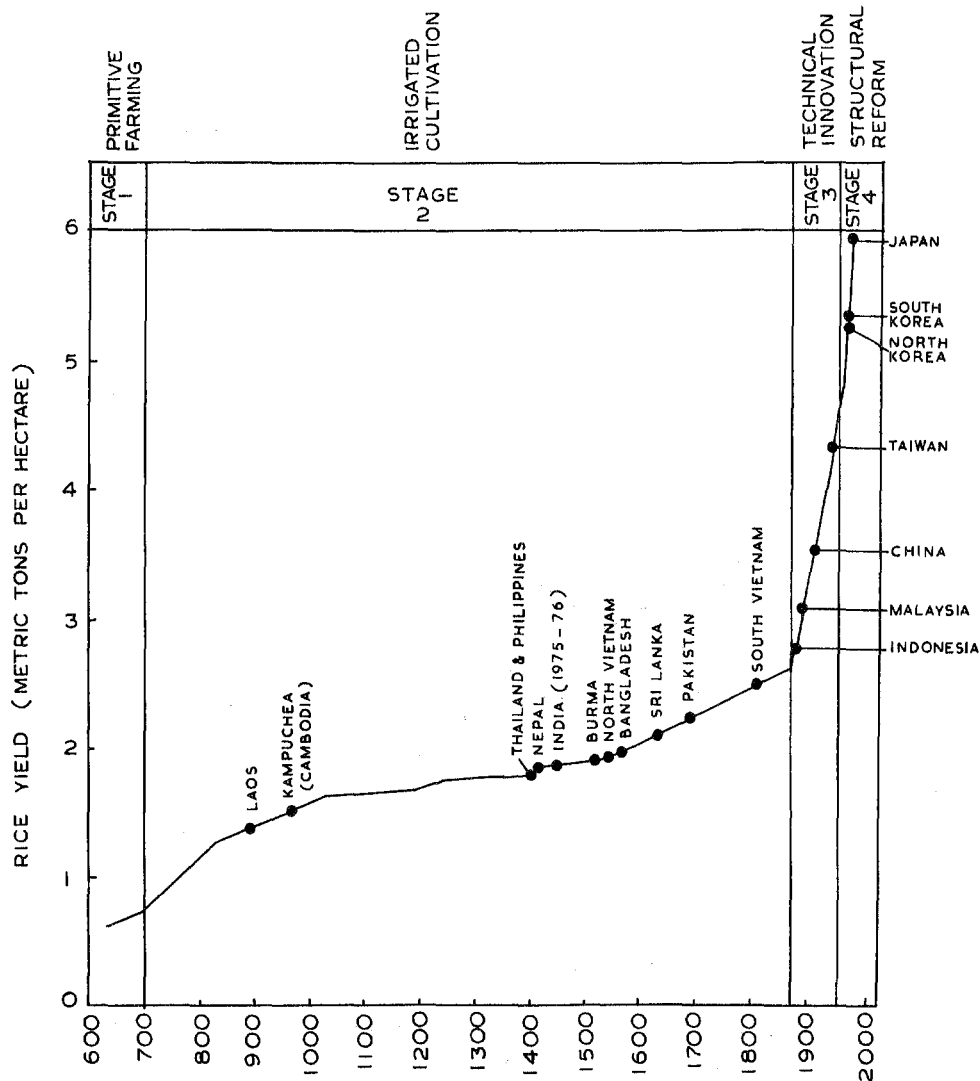


Figure 6. Yield of rice in different countries in Asia in relation to the historic progression in rice yield in Japan. (Source: Asian Agricultural Survey, Asian Development Bank, 1969, p. 520 "Development Strategy on Irrigation and Drainage", by K. Takase and T. Kano.

VARIATIONS IN WHEAT YIELD & RAINFALL

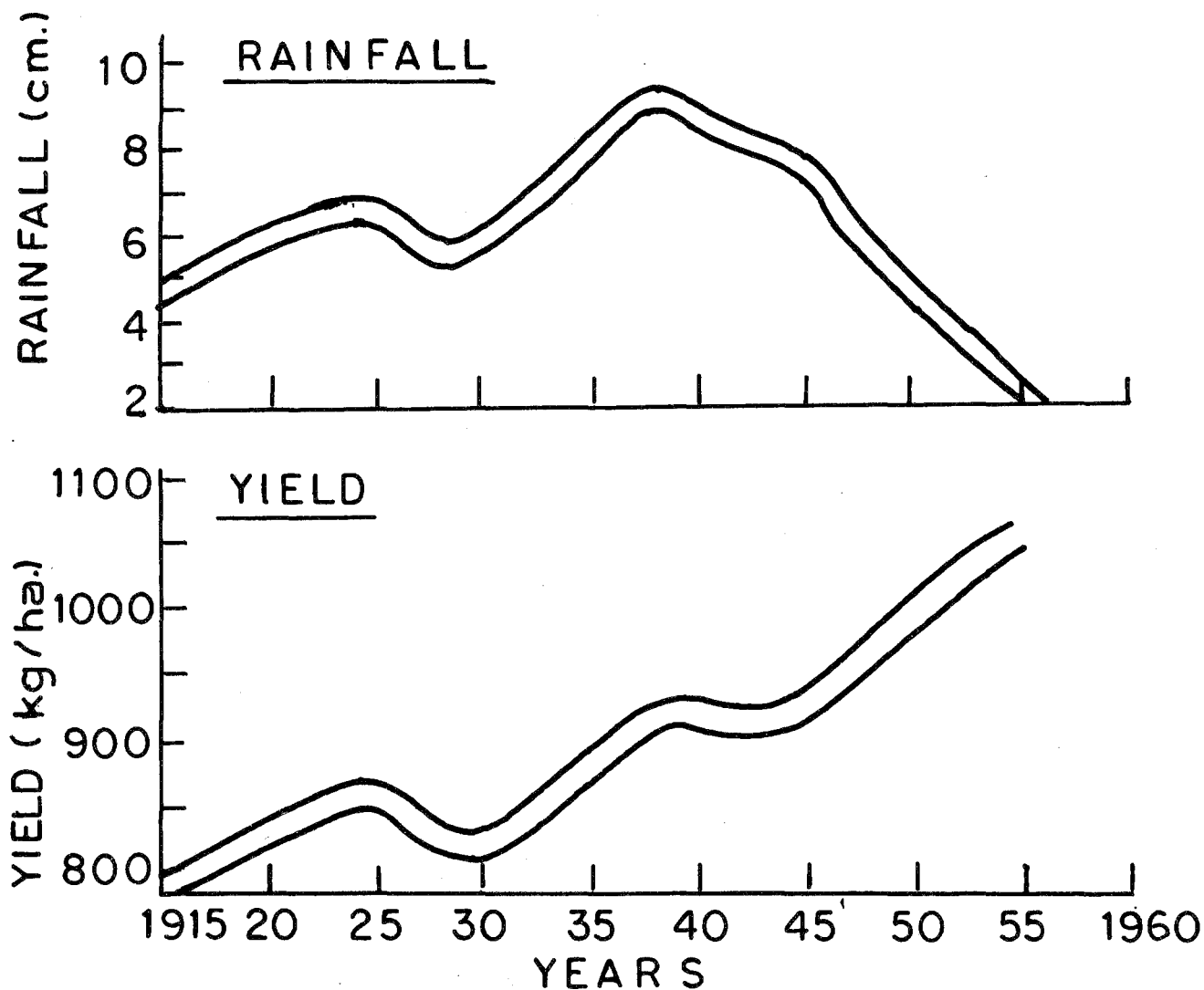


Figure 7. Relationship between rainfall and wheat yield in northwest India showing the impact of irrigation on enhancing and stabilizing yield ^[19].

The availability of a large irrigated area also makes the initiation of additional production programmes in such areas in years of drought or floods possible. Such compensatory programmes in irrigated areas could form an important part of the strategy for minimizing the adverse impact of aberrant weather. The U.S. Department of Agriculture has computed the production needed to build adequate stocks in "good" years to maintain consumption in "bad" years ^[19]. This study also reveals that the largest potential for yield increases is in coarse grain, particularly corn and sorghum.

8.4 Minimizing fluctuations in production in rain-fed and semi-arid areas

The technological approach to imparting greater stability to production in rain-fed and semi-arid areas involves above all measures to conserve the available moisture under a given set of weather variables. By studying the rainfall pattern in detail, including the probable date of commencement of the sowing rain and the likely inter-spell duration between two rains, it is possible to develop more stable cropping systems taking into account the moisture-holding capacity of the soil and the evapotranspiration data [21, 22]. It is also possible to develop contingency plans and alternative cropping strategies to suit different weather probabilities in areas prone to drought and floods. To implement the contingency plans it will be necessary to build seed reserves of the alternative crops. In areas characterized by wide annual fluctuations in rainfall pattern, it is desirable to make the seed reserves necessary for implementing alternative cropping strategies an integral part of the national seed production and storage system [23].

If surplus water can be stored in the watersheds of rain-fed areas, a crop life-saving irrigation can be given if the rainfall stops abruptly at the time of grain development; other crop life-saving techniques are also now available [24]. While the solution both to excess and shortage of water is largely an engineering one, genetic approaches are possible through the development of varieties possessing greater resilience to environmental variables. Thus, Ganga Prasad Rao and co-workers [25] have shown that early maturing hybrids and varieties of sorghum do better during both scanty and abundant rainfall years. Early seedling vigour, hybrid vigour for root growth and quick maturity are attributes which confer on the plant stability of performance in drought prone areas. The cropping strategy for flood-prone areas will have to rely heavily on making the flood-free season the major cropping season.

When meteorologists are able to develop reliable early warning systems of monsoon behaviour, it will be possible to refine further the contingency plans for different weather possibilities and implement them more effectively. Through an integrated approach to efficient water and soil conservation and management in each watershed area, crop planning based on both yield and stability characteristics, introduction of crop life-saving techniques when necessary, and preparedness for introducing alternative land use strategies according to weather conditions, it is now possible both to elevate and stabilize crop production to a greater extent than was considered possible some years ago.

8.5 Fluctuations in production arising from pest epidemics

Besides weather aberrations, the incidence of pest epidemics has been a major factor in causing instability and risk in crop production. Both weather conditions favourable to the pest as well as man-made causes like unscientific crop planning, cultivation of large areas with a single strain of a crop and improper or inadequate plant protection measures can result in widespread pest epidemics. The following are some of the major famines or food losses associated with pest epidemics in the past:

- (a) The Irish famine of the 1840s due to the potato leaf blight epidemic;

- (b) The wheatless days of 1917 in the U.S.A. due to stem rust epidemics;
- (c) The Bengal famine in India in 1943 associated with the Helminthosporium brown spot disease of rice;
- (d) The devastation of all Victoria-derived oats in the mid 1940s in the U.S.A. due to a fungus causing the Victoria blight disease;
- (e) The southern corn blight epidemic caused by Helminthosporium maydis on all U.S.A. maize hybrids carrying the T-type cytoplasmic male sterility during 1970-71;
- (f) The rapid shift from brown planthopper biotype 1 to biotype 2 during 1974 to 1976 when large areas in the Philippines and in Indonesia were planted to a few semi-dwarf strains of rice;
- (g) Downy Mildew epidemic in pearl millet caused by Sclerospora graminicola in India in 1973.

Whereas uniformity within a crop leads to genetic vulnerability, reinstating genetic diversity is one of the most effective means of providing protection against such vulnerability [26]. On the other hand, the sequential release of resistant varieties based on major gene-controlled vertical resistance could lead to the "boom and bust" cycles. Hence, an integrated pest management strategy will have to be developed for each major crop and agro-climatic region. Studies on the relationship between weather and pest epidemics and the establishment of pest survey and surveillance systems at the national and regional levels (as for example, the FAO-sponsored Locust Warning System) can help in taking timely action against pest epidemics. Varietal diversification, gene deployment and other pest containment strategies can be very effective in the control of important diseases like wheat rusts. Satellite photographs of cloud movements also provide a basis for predicting the zone of early establishment of stem rust of wheat in India [27].

Countries in the tropics and sub-tropics face more serious pest problems since there are crops and vegetation through the year serving as alternate hosts to many pests. Also, temperature, sunlight and moisture conditions promote continuous multiplication of pests without interruption, unlike in the temperate areas where the severe winter is a restraining factor. This will be evident from the following comparison of the magnitude of disease problems in the temperate and tropical regions.

Tropical countries will therefore have to devote considerable research and development attention to insulate crops from severe devastation by pests. For developing reliable disease forecasting procedures, the integration of meteorological data with field survey data is essential. Such an approach could lead to other beneficial results. For example, healthy seed potato is now being produced in the plains of North India as a result of the finding that during certain months of the year aphids, which serve as vectors of several virus diseases, are absent [28].

Table 9

Crop diseases in temperate and tropical regions

<u>Crop</u>	<u>Number of Diseases reported:</u>	
	<u>Temperate zone</u>	<u>Tropics</u>
Rice	54	500 to 600
Maize	85	125
Citrus	50	248
Tomato	32	278
Beans	52	250 to 280

8.6 The role of public policies in ensuring stability of production

In the ultimate analysis, farmers grow food or other crops to earn income, in addition to satisfying their home needs. Hence, except in countries where land use planning is controlled by the State, farmers' choices of crops are largely based on the net returns per hectare as well as the extent of risk involved. High yield potential-cum-low risk crops will hence receive much greater acceptance than high yield potential-cum-high risk crops. To sustain agricultural progress at a desired level, it is necessary to support a package of economically viable technology with appropriate packages of services and public policies. Though the production technology associated with dwarf and fertilizer-responsive varieties of wheat and rice itself does not possess built-in seeds of social discrimination, small farmers will be able to derive economic benefit from such technology only if their inherent handicaps in mobilizing the necessary inputs and in taking risks are removed through the provision of appropriate services including credit. The public policy package will have to include appropriate land reform measures, integrated input and output pricing policies and effective marketing, storage and distribution.

Price incentives can stimulate rapid advances in production, as happened in Japan in the case of rice. However, unduly high grain prices will defeat the very purpose for which more food is produced, namely to feed the hungry. Hence, other compensatory benefits may have to be given to small farmers so as to enhance their income without making prices unreasonable to the consumer. Also, it will be desirable to develop an agricultural credit insurance system, which can protect farmers from weather risks such as hailstorms, typhoons, floods and drought. For developing an effective credit insurance programme for different farming systems, there will be need for joint research between meteorologists and agricultural scientists.

8.7 Constraints analysis

Another important contribution Governments can make to help farmers to realise full economic benefits from the untapped production reservoir which exists even at current levels of technology in the major farming systems, is to sponsor

multi-disciplinary analyses of the constraints responsible for the gap between potential and actual yields. Some of the major groups of constraints which determine the size of gap are indicated in Figure 8. The relative importance of each component will vary from area to area and suitable weightages can be developed on the basis of a careful study. A study of this kind carried out by the International Rice Research Institute in several Asian countries has revealed the important constraints to high yields in rice [29]. Meteorologists, agronomists, economists and statisticians should undertake similar joint studies in all major farming systems. Recent estimates of the ultimate potential for increase of land area for agricultural use are summarized in Table 10. The data are from the World Bank report on Agricultural Land Settlement published in 1978 and summarized in Ceres [30].

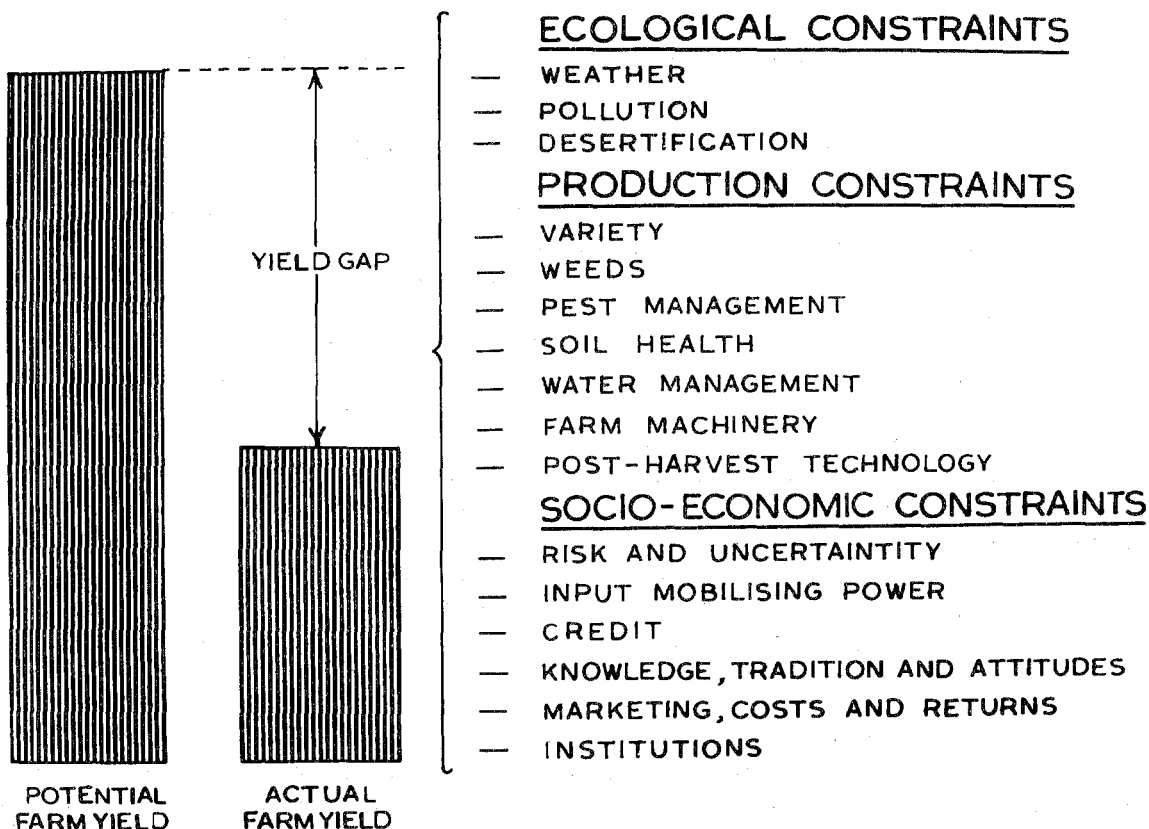


Figure 8. Major constraints causing a gap between potential and actual farm yield at current levels of technology in field crops.

Table 10

Potential for increase of land area for agricultural purposes (in '000 hectares)

Region	Land under agriculture in 1976	Estimated poten- tial for increase	Percentage of world total pot- ential for increase
North America	232 097)		
Western Europe	96 184)		
Eastern Europe and USSR	278 574)	181 43	18.04
Oceania	46 019)		
Africa	185 610	280 390	29.92
Latin America	143 568	442 432	44.06
Near East	81 062	30 938	3.08
Asian Centrally Planned countries	141 266	62 734	6.25
Far East	266 329	5 671	0.56

It will be observed from the data in Table 10 that some of the densely populated regions of the world like the Far East have very little scope for increasing the area under cultivation. Hence the only pathway of agricultural advance open to them is productivity improvement. For achieving this, data from constraints analysis will be very useful. Similarly, in areas with great potential for bringing more land under cultivation, as Latin America and Africa, an analysis of constraints and consequences (particularly from the ecological standpoint) will be helpful to the policy makers in arriving at priorities in investment.

8.8 Effect of climate on aquatic productivity

It is well known that the success of fish catch in any particular year depends on the effective recruitment during the previous seasons through proper spawning and survival of the young. The influence of climate on the breeding of many fishes in the tropics is seen from the spurt of spawning activity and a general increase in the number of fish eggs in the marine plankton soon after the first outbreak of the rains. Such intensive spawning associated with climatic changes is even more pronounced in freshwater fishes whose spawn occur in abundance during the floods. There is, however, need for intensive research on the relative role of different environmental parameters in determining the size of fish stocks if reliable systems of forecasting are to be developed. The quantitative relationship between temperature and fish yield also needs to be elucidated under different environmental conditions. Interrelated systems like the Peruvian anchovy and El Niño and the oil sardine and the monsoons in the Indian Ocean provide opportunities for multi-disciplinary research. (See also overview paper by Cushing.)

Besides research on the methodology for early warning and yield-forecasting services, it is necessary that more detailed knowledge be developed on the management of both ocean and freshwater resources. The scientific management of aquatic

resources based on principles of ecology and economics is as important in fisheries as the scientific management of soil, water and air resources in crop and animal husbandry. If this is not done, aquatic desertification leading to the destruction or diminution of the biological potential of water caused by pollution, over-fishing and other man-made processes can occur.

9. Global food production: challenges and opportunities

9.1 Challenges

The relentless growth in population, particularly in poor nations, following rapid advances in preventive and curative medicine in recent years (Figure 9) poses the greatest challenge not only for producing the needed quantity and quality of food for the existing and expanding population, but also for generating the economic growth rate essential for full employment. Agricultural growth will henceforth have to be viewed not merely in terms of the production of certain quantities of food but also in terms of employment and income generation in the rural areas.

Another major challenge is the preservation of the renewable nature of our renewable resources. This can be done only if the entire community in each country co-operates in ensuring that there is no depreciation in basic agricultural assets. Unfortunately, this awareness is yet to become widespread.

A third major challenge is in the area of energy supply and management in agriculture and aquaculture. Technologies will have to be developed and promoted which involve organic recycling principles and integrated approaches to pest management and nutrient supply. When solar power becomes economically attractive, new vistas in production can be opened up by combining the use of solar energy for a variety of purposes during the production and post-harvest phases with techniques like no-tillage or minimum-tillage and other methods of minimizing the energy input needs.

A fourth area of considerable significance is the development of crop-livestock integrated production systems. While livestock production has assumed importance in rich countries to meet the dietary preferences of people, the integration of animal husbandry with agriculture has become essential in many MSA countries since this is the only immediately feasible method of enhancing the income of small farmers and reducing under-employment among landless labour. How can this situation be reconciled with the much higher energy needs of the plant-animal-man food chain to which a reference was made earlier? Obviously, technologies of livestock management based on a complementary relationship between animal and man need to be developed. Mixed farming has always been a way of life with farmers in many developing countries. The ruminating animal is ideal for such a symbiotic production system, since all cellulosic material which cannot be digested by man can be suitably fortified and converted into nutritious animal food. Crop-livestock-fish integrated production systems offer even greater opportunities for achieving high energy input-output ratios 31.

A fifth area of immediate relevance to the food problem is the initiation by governments of appropriate programmes for deriving benefit from the untapped yield reservoir existing at current levels of technology. This will call for massive efforts in education, organization of relevant services based on constraints analysis and, above all, in introducing public policy measures which would stimulate both production and consumption.

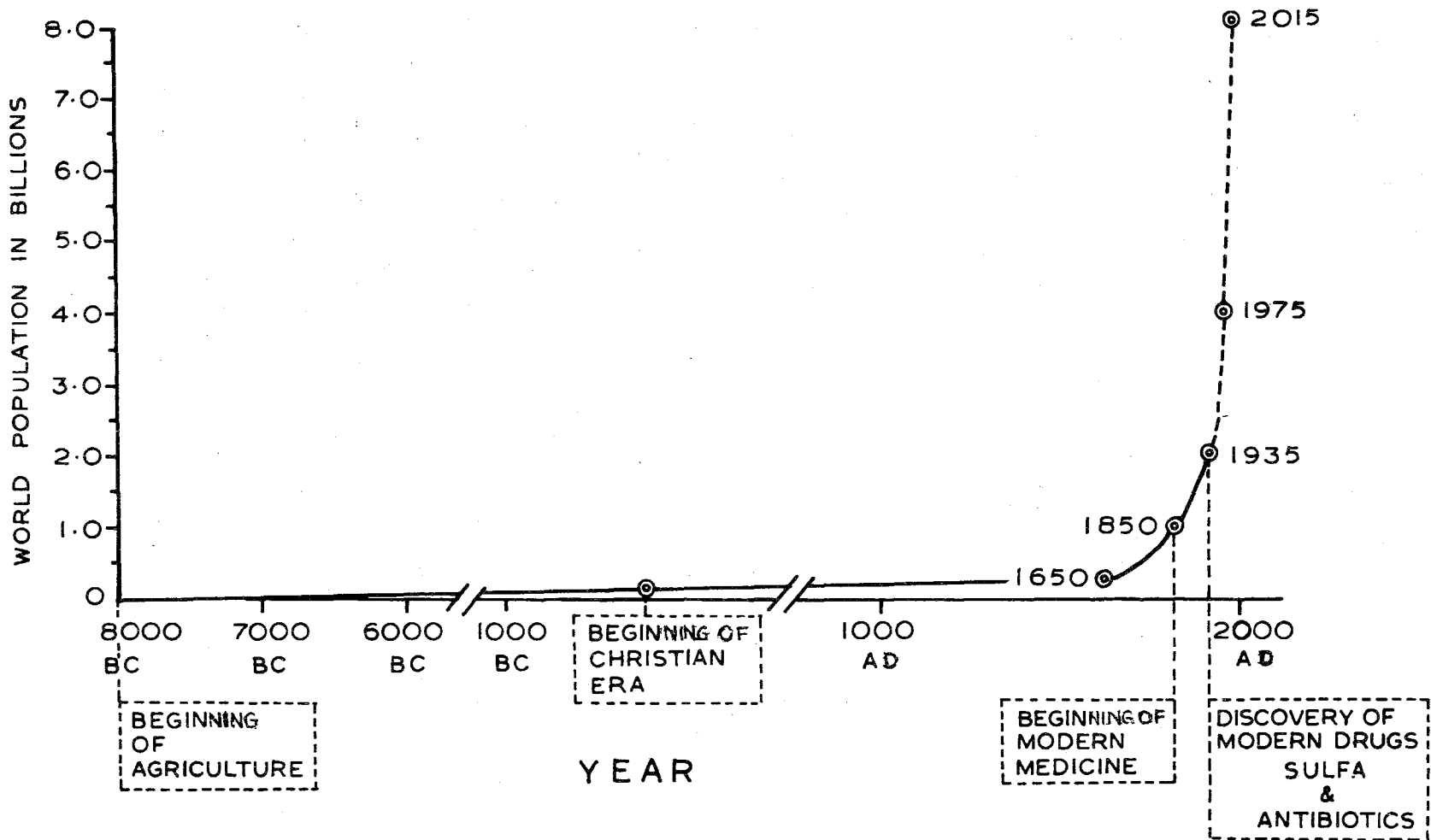


Figure 9. Trends in population growth

Finally, governments will have to grapple with the challenge of distribution. As would be evident from the data presented earlier, the world food production is sufficient to feed the millions who are malnourished today provided there is equitable distribution. The deadline of 1984 set by the World Food Conference for ensuring that no human being goes to bed hungry can be advanced even to 1979, if a new age of humanism can be superimposed on the era of science and technology. Unless this happens, global action to meet man's need for food, energy and other basics may not be forthcoming. Until all global planning for the future and all development of technology are subjected to the one test prescribed by Mahatma Gandhi, "Will this benefit the poorest men?", it is unlikely that an international food security system will come into existence (Figure 10). The prevailing condition where with every rise in Gross National Product, the poorest nations and income groups within nations suffer more due to the increased demand for food by wealthier nations and wealthier groups within nations can be altered only by public policies designed to bring about equitable distribution ^[32]. How can each nation proceed to build a national food security system which can insulate the people of the country from hunger arising from weather-induced crop failures and/or inadequate purchasing power?

9.2 Opportunities

While available projections of population, per capita income and demand for food on the one hand and production and marketable surplus of food on the other, reveal a possible global food gap of about 45 million tonnes by 1985, the encouraging sign is the growing awareness among developing countries that agriculture needs and deserves over-riding priority. National, regional and global efforts in agricultural research and development are growing. The Consultative Group on International Agricultural Research sponsored by FAO, UNDP and IBRD and supported by many nations, banks and foundations is financing a global grid of research centres designed to advance the pace of technology development in major food crop and livestock production systems in developing countries. Analysis of gaps and constraints in major crop production systems in several MSA countries has shown that while the gap between potential and actual farm yields is high, the constraints can be remedied fairly speedily. Global weather monitoring programmes sponsored by WMO are also making rapid progress and agro-meteorology is emerging as a major science. Yield forecasting techniques are being perfected. Weather satellites and remote sensing techniques have added a new dimension to research in this area. Hence, reliable early warning systems of likely food shortage can be developed if there is adequate international co-operation. The time is therefore appropriate for governments to launch a programme to build strong national food security systems. Once national food security systems are developed, it will be relatively easy to build an international food security system.

9.3 Components of a national food security system

The following are some of the major components of an effective national food security system:

- (a) Ecological security;
- (b) Technological security;

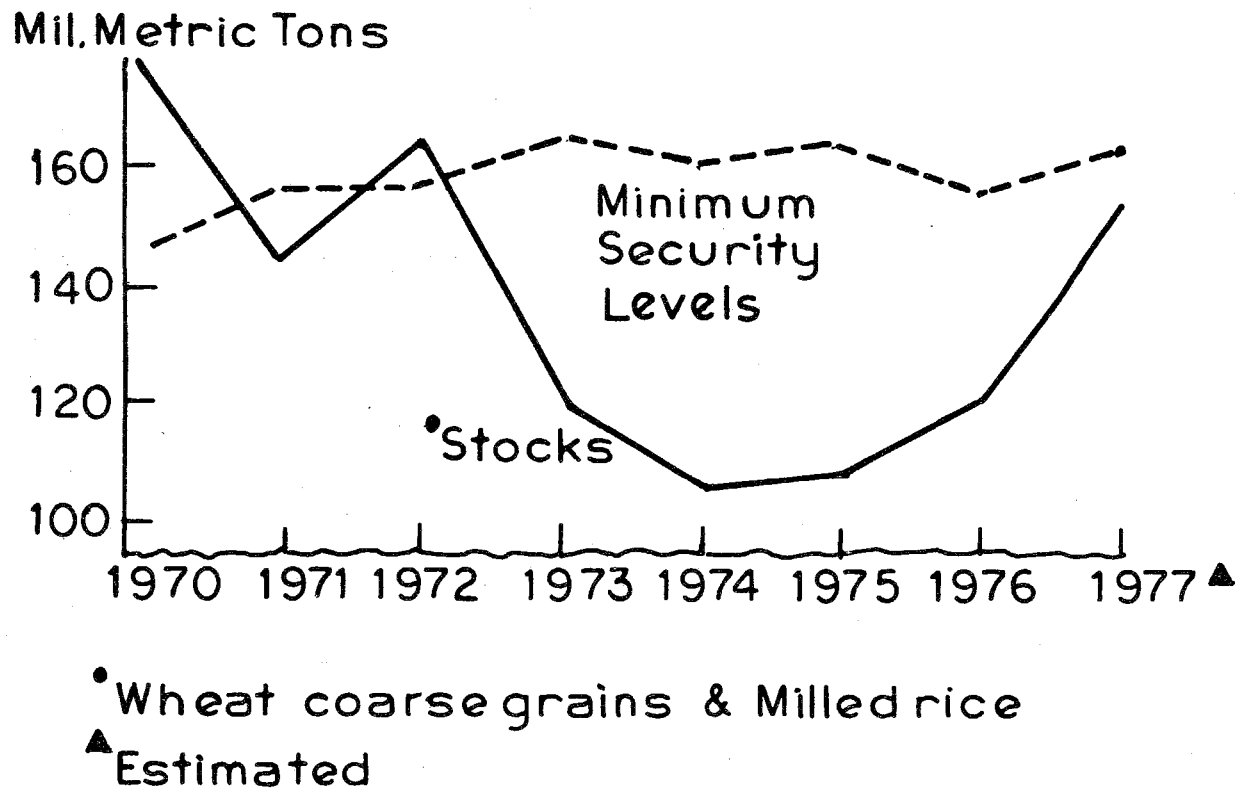


Figure 10. World carry-over stocks and minimum security levels (excluding U.S.S.R. and People's Republic of China) 18.

- (c) Building up food reserves;
- (d) Social security.

9.3.1 Ecological security

If the ecological infrastructure necessary for sustained agricultural advance is not preserved and strengthened, desertification processes will damage both agriculture and aquaculture. Nothing should be done which will cause unfavourable changes in the macro- and micro-environment. To achieve this, there is need for a national movement in every country for promoting economic ecology ^[33]. Economic ecology, unlike strictly conservation ecology, is intended to maximize the economic benefits from a given ecological milieu and to minimize the risks and hazards characteristic of that environment. Guidelines for achieving ecological security along with agricultural progress will have to be drawn up by an inter-disciplinary team of scientists for each area.

9.3.2 Technological security

Technology development should be tailored to specific ecological, economic and social conditions. It should be ensured that the technology does not possess built-in seeds of social discrimination. The major aim of technology in countries with very little scope for bringing additional land under cultivation should be to increase continuously the economic yield per hectare of land or water surface without detriment to the long term production potential of soil and water. Also, productivity improvement has to be brought about without increasing heavily the consumption of non-renewable forms of energy. The improvement of yield should not also be at the cost of stability of production. Where the probability for weather-induced instability in yield due to causes like flood and drought is high, alternative cropping strategies and crop life-saving techniques should be developed to suit different weather models. Post-harvest technology should receive as much attention as production technology so that both the farmer and the consumer derive full benefit from the products marketed.

An area of technological security which has yet to receive adequate attention is the introduction of a systems approach in R and D efforts. The following are a few of the major farming systems which need attention particularly in countries where land is a limiting factor in expanding production:

- (a) Multiple cropping systems in irrigated areas

It is possible to take 3 to 4 crops in the same plot of land in a year in the tropics and sub-tropics with photo-insensitive and quick maturing varieties of different crops. It is, however, necessary to pay adequate attention to the maintenance of soil health and fertility, prevention of pest build-up and grain drying and storage. Instances of liver ailments arising from aflatoxins in the grains of varieties which mature before the rains stop are growing.

(b) Rain-fed farming

Research programmes in semi-arid areas should lay stress on water and soil conservation and scientific land use planning. Detailed knowledge should be gathered on the likely date of commencement of sowing rains, inter-spell duration, evapotranspiration and moisture holding capacity of the soil.

(c) Orchards and garden land cropping

In the case of fruit trees, plantation crops and forest trees, it is possible to design an efficient 3-dimensional canopy involving both the horizontal and vertical spaces. An efficient canopy should promote co-operation among the crops grown together. Thus, in such areas the efficiency of farming will have to be measured by the effectiveness with which the air space is used in addition to soil and water. Since multi-level or 3-dimensional cropping is likely to assume increasing importance when the pressure of population on land increases (the situation being analogous to the spread of sky-scrapers in city architecture), intensive research on the micro-environment in 3-dimensional canopies is necessary. Coconut, cocoa and pineapple form a good co-operative combination from the point of view of efficient utilization of sunlight, water and nutrient in several tropical areas.

(d) Mixed and inter-cropping

In such systems, some of the factors promoting efficiency and stability of production are:

- (i) efficient interception of sunlight;
- (ii) ability to tap nutrients and moisture from different depths of the soil profile;
- (iii) non-overlapping pest sensitivity; and
- (iv) introduction of legumes for promoting biological nitrogen fixation.

(e) Kitchen gardening

This can take the form of growing vegetables and fruits, backyard poultry farming and home fish gardening. When designed properly, a very high return of food calories for every calorie of cultural energy invested can be obtained, thus making substantial contributions to the improvement of nutrition.

(f) Agro-forestry

In addition to promoting commercial, social and other forms of forestry, there is need for more research on inter-cropping in forest canopies. Agro-forestry is a sustainable management system for land which increases overall production, combines agricultural crops, forest plants and animals simultaneously or sequentially.

(g) Mixed farming

Mixed farming systems may involve crop-livestock, crop-fish, livestock-fish and crop-livestock-fish integrated production systems. These can be of great value to farmers with small land holdings for maximizing income and employment.

Plant and animal breeders should adopt a cafeteria approach in the selection of genotypes of crops and farm animals for the different farming systems referred to above. Production agronomists also should adopt a cafeteria approach in developing technologies suited for farmers with varying input-mobilizing capacity. Meteorologists should measure the impact of different weather parameters on the entire system and not just on components of it if their data are to be of use in designing more efficient systems. Farming System Meteorology will involve much greater attention to the micro-environment in crop canopies and to the matching of sequential use of land with weather conditions which are conducive to the optimum performance of the crops and animals farmed either concurrently or consecutively.

9.3.3 Building up food reserves

Every MSA country should try to build a grain reserve which can help it to meet the anticipated shortfall in a bad year as well as to run an effective public distribution system. Countries which are not normally self-sufficient in their food requirements will obviously have to maintain adequate stocks by imports so that in years when the production is adversely affected by weather in the traditional food exporting countries, prices are not allowed to rise abnormally. Every country will have to devise an appropriate grain reserve policy based on ecological, economic, logistic and other considerations. The reserve may not be only of cereals but may include millet, grain legumes, oilseeds and other crops depending on needs and availability. Such a buffer stock operation can also help to ensure that prices of farm produce do not fall below an economic level. In addition to maintaining a basic reserve and sufficient operational stocks, it will be prudent always to keep in readiness plans for increasing the production from irrigated areas during years characterized by widespread drought. Thus, an integrated grain reserve policy and a programme for the efficient use of the reserve in production potential during emergencies on the basis of early warning from crop-weather watch groups should help to launch every country on the path of self-reliance in food.

9.3.4 Social security

A mismatch between the ability to grow food and the ability to purchase and consume it on the part of large numbers of people could lead to a situation where

a country may have large grain reserves but many children, women and men may still go to bed hungry. Hence, social security measures which ensure that everyone has his daily bread are important. Depending on social conditions, such measures could take the form of "Food for Work", employment guarantees, minimum wage, etc. Social security measures should not be based on dole and patronage concepts but should aim at providing opportunities for earning a minimum wage. Under conditions of sudden disasters, relief and nutritional intervention programmes will be essential ^[12]. Social security measures should not only cover consumers but farmers also. Through integrated pricing policies, farmers should not only be assured a fair price for their produce but also articles of daily consumption in rural areas at a fair price. Small farmers will also have to be insulated against risks arising from aberrant weather through an appropriate insurance system.

10. Conclusions

Future developments in solar energy utilization, genetic engineering and weather forecasting and modification could open up altogether new vistas of terrestrial and aquatic productivity. However, while working and waiting for such breakthroughs, no time should be lost in building dependable and effective national and international food security systems based on known knowledge and technology. Given appropriate political decisions and resource back-up, this task can be accomplished by 1984, the target year set by the World Food Conference held in Rome in 1974 for banishing hunger from the Earth. The finite resources of the "Spaceship Earth" (to quote Buckminster Fuller) can provide food, clothing and shelter for all provided the resources are conserved and utilized by all countries in a manner that will generate synergy and symbiosis ^[34]. This will call for a highly co-operative interaction between those who serve science and those who move society as well as among both scientists belonging to different disciplines and social leaders belonging to different political ideologies.

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CLIMATIC VARIABILITY AND AGRICULTURE
IN THE TEMPERATE REGIONS

James D. McQuigg*

1. Introduction

The issues which will be presented in this paper are the result of important interactions of the temperate zone agricultural system with year-to-year climatic variability. It is quite likely that the papers presented by other overview speakers on tropical and semi-arid agriculture will contain some of the same ideas, for many of the major agricultural issues of these regions are also the result of factors and forces that are worldwide in scope.

There are two ways to view the issues raised in this paper:

- (a) The design and operation of systems to collect and distribute climate information are matters of concern to the directors of national weather service organizations and to their staffs who need to match their resources with the demands for services that are presented.
- (b) The users and potential users of climatic information need to be concerned about the kind of system that will produce the flow of information they will need in the future. It is possible that some of this information is already being generated but not being used effectively. This is a problem that agriculturalists, business managers and government officials will need to solve.

The temperate zones contain a large share of the world's fertile soil. In recent years, countries with temperate climates have produced about 75 per cent of the world's exportable wheat and coarse grain, the latter term including rye, barley, oats, corn (maize), sorghum, millet and mixed grains. A sample of such countries, representing a little over half of the world's total cultivated land area, produced about two-thirds of the world's total grain in recent years.

It is true that important improvements have been made in tropical and semi-arid zone agricultural production, and it is also true that these improvements will

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continue to be made in the future. It is nevertheless quite likely that the major source of exportable grain will be the temperate climate zones for many years to come.

At this point it may be helpful to discuss briefly the meaning that may be attached to the term "agriculture". Agriculture has been defined as an activity that takes place within a shallow layer of soil and atmosphere. Agricultural meteorologists, therefore, have centred most of their attention on the activities that take place on farms and ranches. However, a more useful definition of agriculture would include the activities mentioned above with the addition of various activities within governments, business organizations, educational institutions, and research installations. Marketing, storage, transport, and financing decisions influence the the availability and price of agricultural products. There are times when the impact of climatic variability on the off-the-farm activities is at least as important as its impact on growing plants and animals. The term "agricultural system" might be applied to this larger concept.

It will be noted that this paper deals primarily with the production of wheat and coarse grain, the latter being largely used for feeding livestock. There are two reasons for this emphasis on cereal crop agriculture:

- (a) world trade in grain is becoming increasingly important relative to other forms of food; and
- (b) the data base on yield, area involved, and production is better for cereal agriculture than for pastoral agriculture.

However, many of the issues that will be discussed in connexion with cereal agriculture also apply to pastoral agriculture, and many of the opportunities for effective use of climate information that will be used as illustrations also apply in a pastoral setting.

Finally, while the author's experience has been largely with United States agriculture, there is ample evidence that the main issues there are common to the agricultural systems of both the developed and developing countries in the temperate zones elsewhere in the world.

2. Impact of climate and agricultural development on yields.

The application of scientific, technical, and managerial knowledge to agriculture has resulted in significant increases in grain yields over the past three decades. These increases are without precedent in human history. They have made it possible to meet the increasing demand for food, but they have also caused some problems that still need solution. In the most recent few years there is evidence that the trend in yields has flattened out, or at least slowed down. Is this latest change the result of less favourable weather? Has agricultural production reached a plateau? Projections of future grain yields and production must be based on realistic projections of both future climate and future agricultural development.

2.1 The importance of temperate zone agriculture

The temperate climate regions of the world include some of the world's most productive soils. A sample of countries that fit into this climatic category had close to 75 per cent of the world's area devoted to wheat and coarse grain production in 1976 and 1977. In these same years, a little more than 80 per cent of the world's wheat and coarse grains came from these same sample countries.

The percentage of total world grain production that is exported from the country of origin has increased from about 10 per cent in the late 1960's to close to 13 per cent in the last few years. A very large share of this exportable grain came from countries with temperate climates.

World consumption of grain has risen significantly over the last few decades. The consumption of wheat and coarse grain was running close to 820 million metric tons in the mid-1960's. In the mid-1970's, this figure was close to 1035 million metric tons. Production has risen, but with some variability in the amount of increase from year to year, as weather conditions have varied. The yearly differences between production and consumption for the last twelve years are shown in Table 1.

Table 1

World Production Minus Consumption
(Millions of Metric Tons)

Production Year	All Grains	Wheat Plus Coarse Grain
1966	26.1	27.7
1967	19.7	16.4
1968	31.2	28.0
1969	-13.7	-16.3
1970	-39.1	-40.0
1971	17.4	20.1
1972	-41.4	-35.7
1973	6.0	3.7
1974	-11.7	-11.3
1975	5.5	- 0.4
1976	53.5	55.8
1977	24.9	26.4

Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-2-78, February 16, 1978.

2.2 Historical account of yield increases

Most of the discussion in this section will be concerned with a brief historical account of the factors that have led to increased yields of grain. Some

of the problems that must be solved if we are to have the ability to project future grain yields and production will also be presented. These problems are not confined to the temperate zone climates.

The application of scientific, technical, and managerial knowledge over the past three or four decades has resulted in increases in grain yields that are without precedent in human history. Values from a very long series of wheat yield data for the United States are shown in Figure 1 and corn yield data for the United States are shown in Figure 2. Both of these data series exhibit a comparatively flat trend in yields from the previous century through the decade of the 1930's. Following that time, corn yields in the United States have more than tripled and wheat yields have doubled. A shorter wheat yield data series for an aggregate sample of temperate zone countries is shown in Figure 3, and wheat yield data for the U.S.S.R. are shown in Figure 4.

The increase in grain yields over the past three decades has been the result of a complex mix of factors, including:

- (a) improved seed varieties;
- (b) increased application of chemical fertilizers, insecticides, and herbicides;
- (c) more efficient machinery;
- (d) more skilful management;
- (e) interaction of the above factors with a run of more favourable crop weather in some important production regions; and
- (f) expansion of production into less fertile soil regions.

For crops grown under carefully controlled experimental design it is possible to sort out this mix of factors and express the impact of change in each in a quantitative manner. In most instances, however, this is not possible, primarily due to the lack of data. It has been possible, though, to separate most of the impact of year-to-year weather variations on yield by grouping all of the other factors together and incorporating them in a quantitative model. (This works well for the period 1955-1970 because there was a reasonably even trend toward increased use of fertilizer, insecticides, herbicides, better machinery, etc., in many developed agricultural regions.)

2.3 Evidence for a recent change in the trend of yields

A number of agriculturalists and climatologists believe that the trend toward high grain yields that was in progress through the 1950's and 1960's has flattened out, or at least slowed down, since the early 1970's. This appears to be true for United States corn (Figure 5) and for world total grains (Figure 6). Wittwer ¹ has written, "Productivity of the major food crops has reached a plateau. Yields of wheat, maize, sorghum, soybeans and potatoes in the United States have not increased since 1970. This is true of maize, potatoes, wheat and cassava in Latin America.

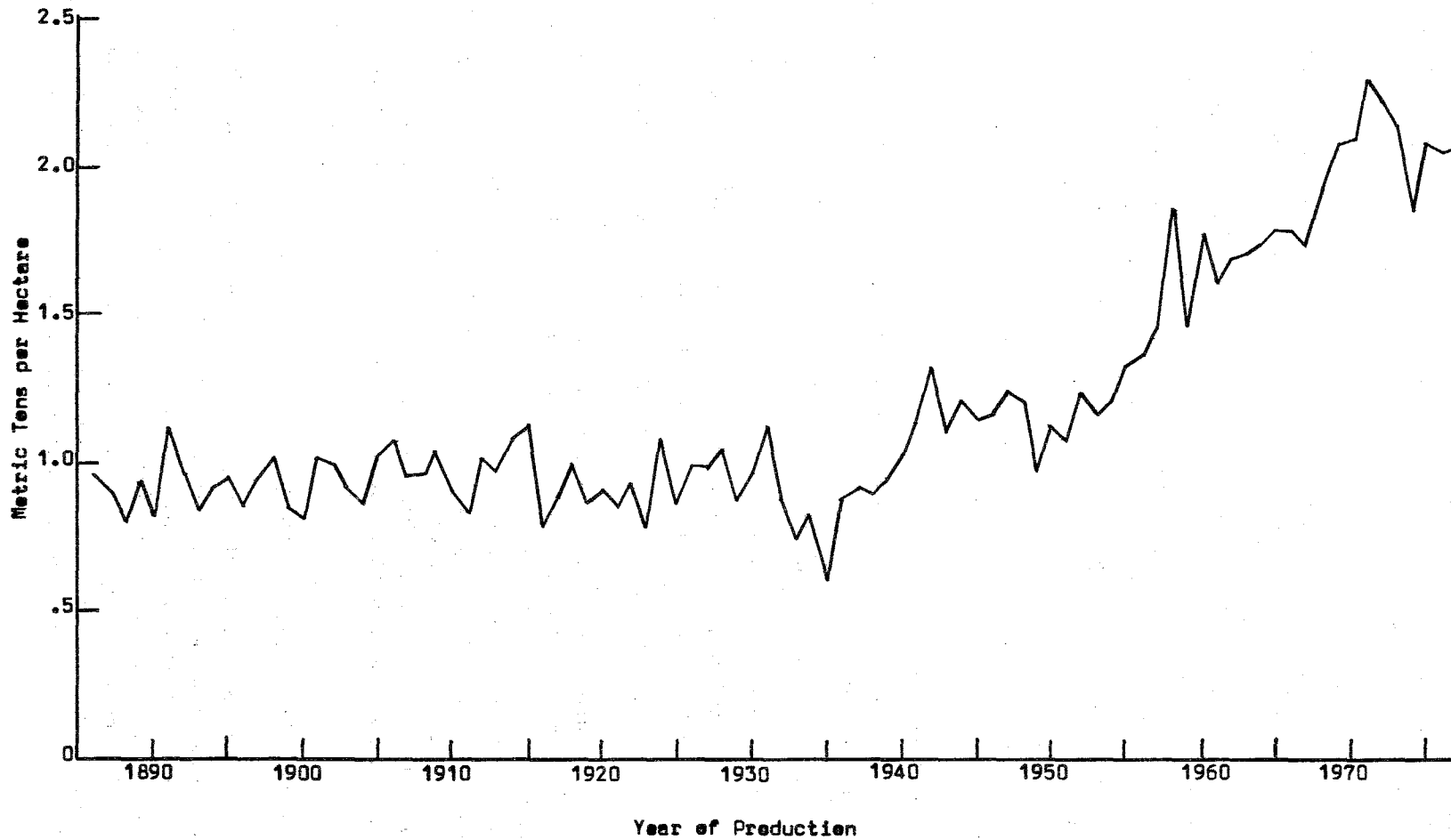


Figure 1. United States wheat yields. Source: U.S. Department of Agriculture Statistical Bulletin No. 101, June 1951, and U.S. Department of Agriculture Agricultural Statistics series.

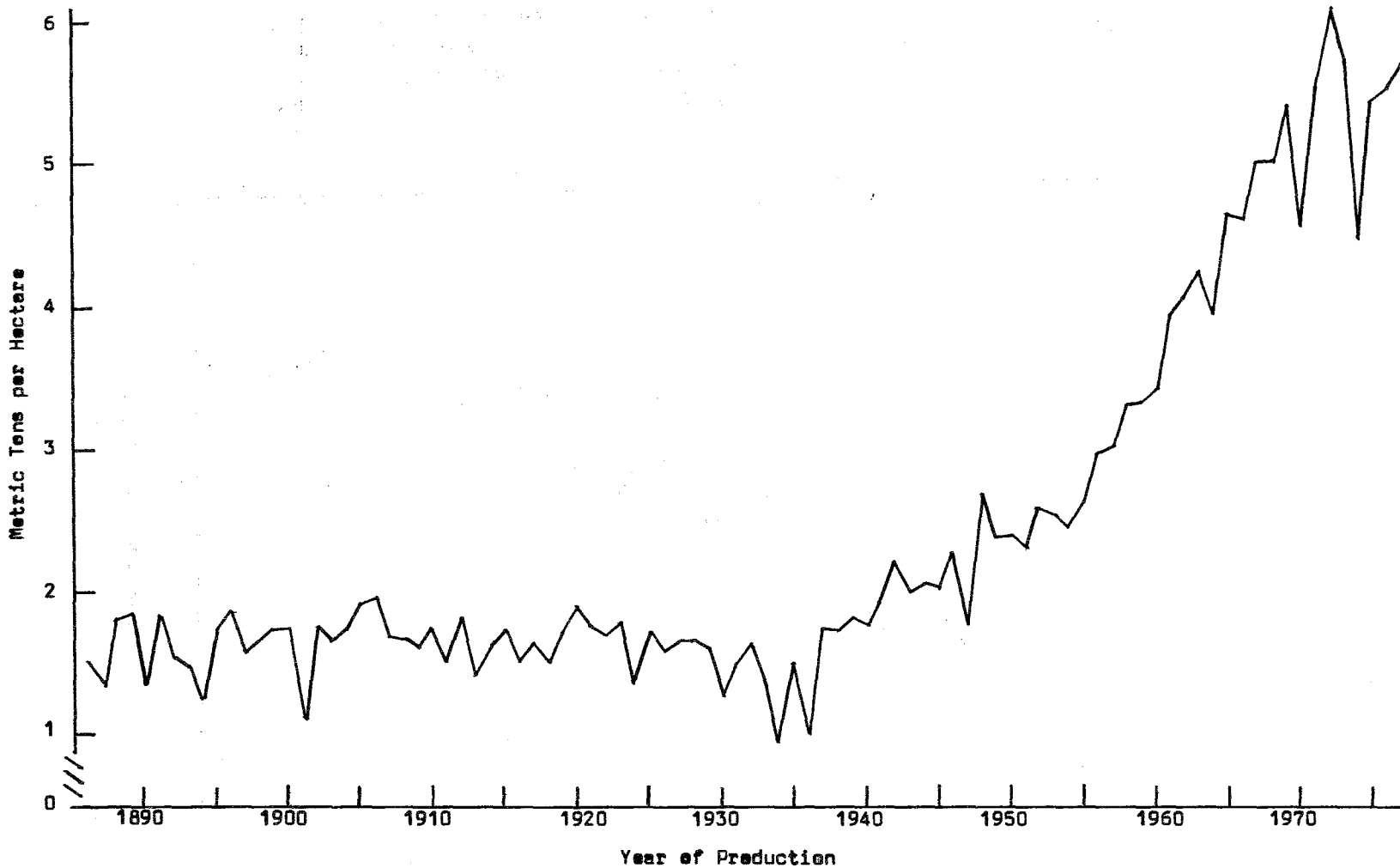


Figure 2. United States corn yields. Source: U.S. Department of Agriculture Statistical Bulletin No. 101, June 1951, and U.S. Department of Agriculture Agricultural Statistics series.

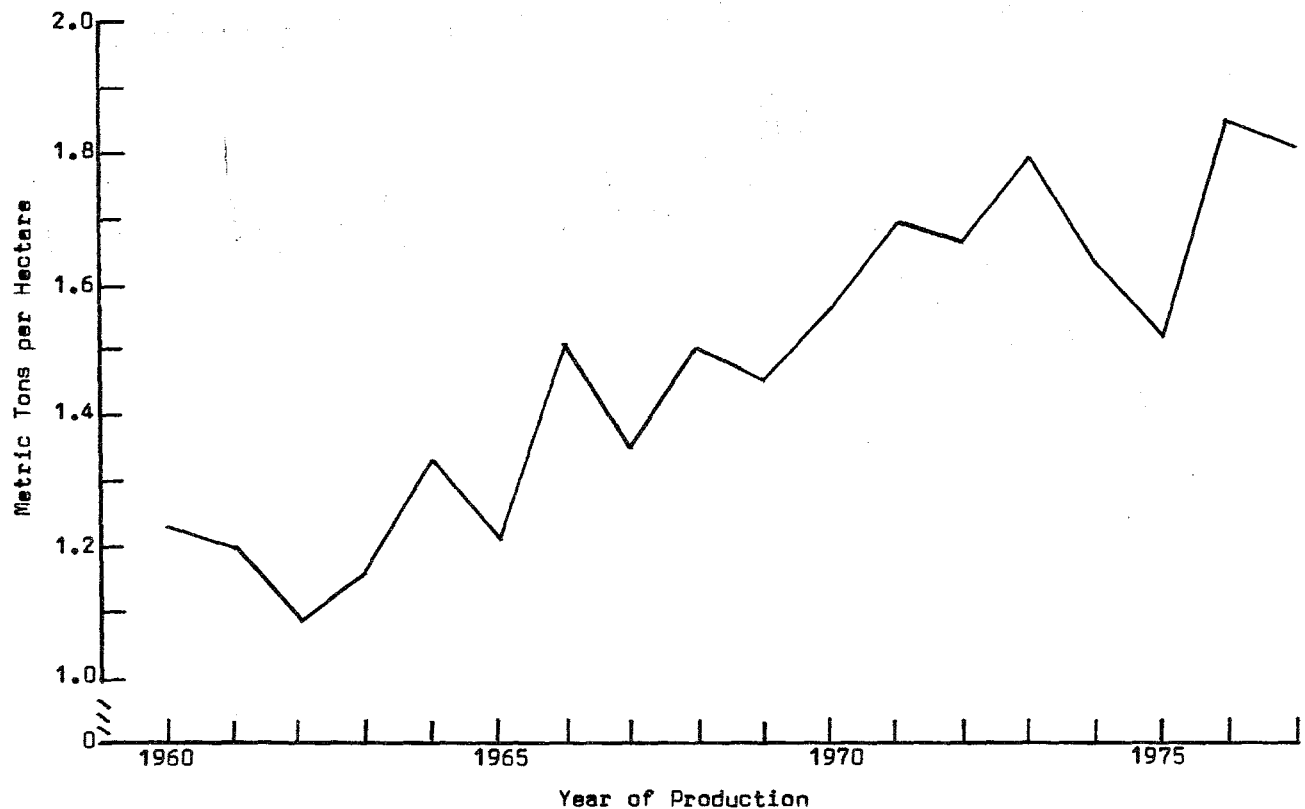


Figure 3. Aggregate wheat yields (Canada, United States, U.S.S.R., China, France, Australia, Argentina, West Germany, United Kingdom, Spain).
 Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-9-76, May 1976, and various 1978 issues.

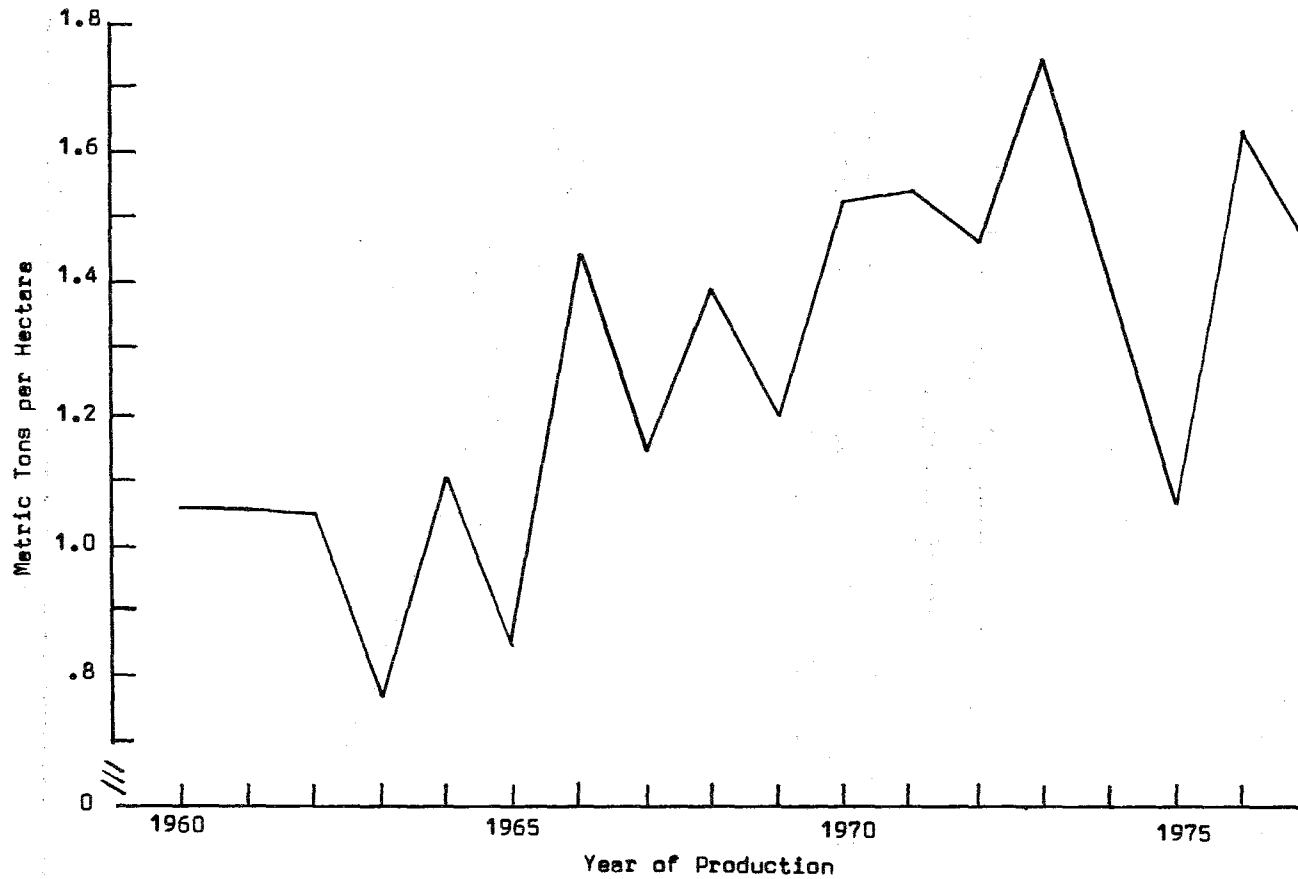


Figure 4. U.S.S.R. wheat yields. Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-9-76, May 1976, and various 1978 issues.

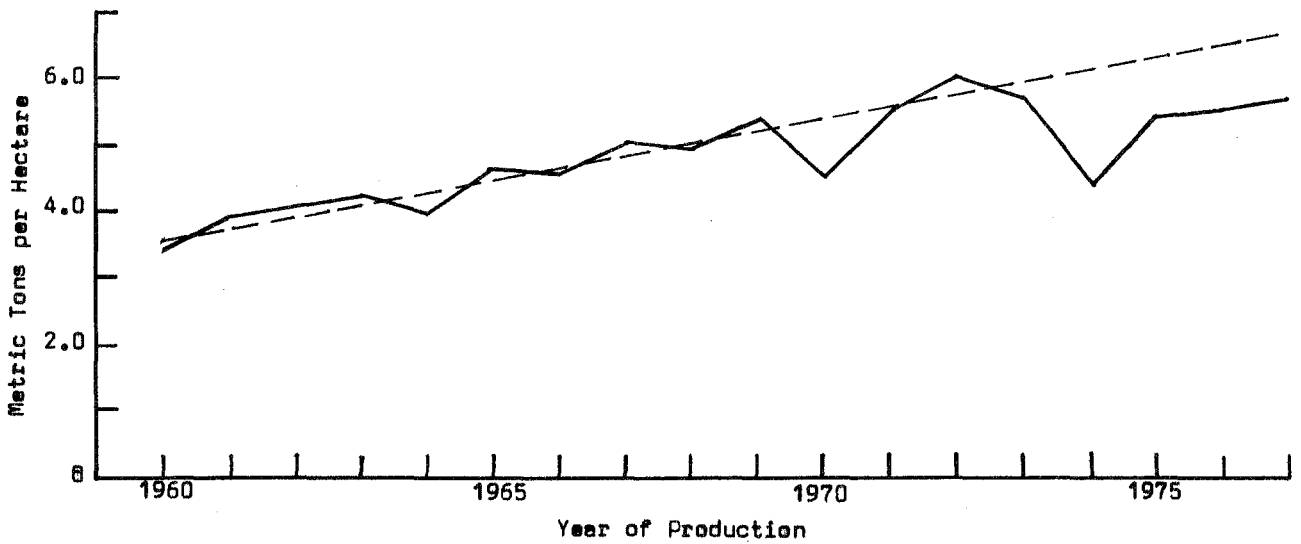


Figure 5. United States corn yields. Source: U.S. Department of Agriculture Statistical Bulletin No. 101, June 1951, and U.S. Department of Agriculture Agricultural Statistics series.

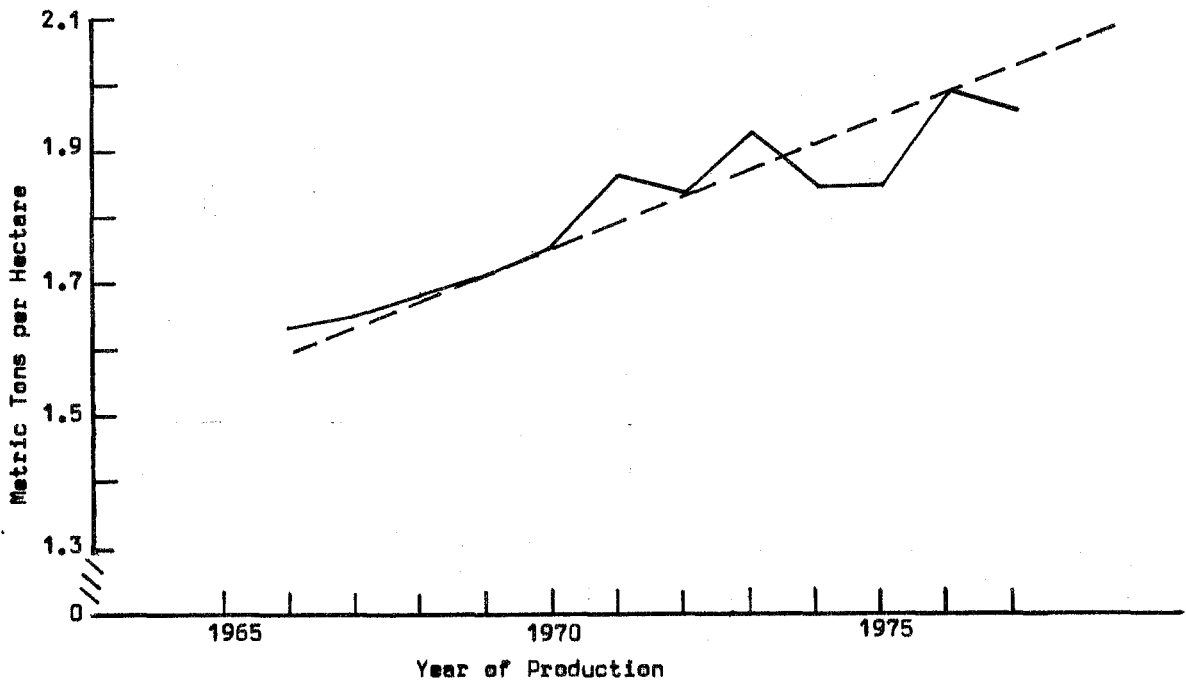


Figure 6. World total grain yields. Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-11-77, July 19, 1977.

World grain yields have declined. Increased production has been achieved largely by cropping more land." Jensen ⁵ has made a strong case for levelling off of grain yields in the developed countries.

It is true that there have been some increases in the amount of land devoted to crops in recent years, in part as a response to increased demands for grain and in part as a response to more favourable grain prices. The data in Table 2 are from a sample of countries that produce wheat in the temperate climate zones. The values have been standardized to the 1960-64 period for comparative purposes.

Table 2
Wheat yield, harvested area & production indexes
 (Canada, United States, U.S.S.R., China, France, Australia,
 Argentina, West Germany, United Kingdom, Spain)

Average of 1960-64 period = 1.00			
<u>Year</u>	<u>Yield</u>	<u>Production</u>	<u>Area</u>
1960	1.023	.983	.973
1961	.998	.899	.980
1962	.906	1.025	.999
1963	.965	.945	.993
1964	1.106	1.148	1.055
1965	1.006	1.042	1.054
1966	1.256	1.316	1.061
1967	1.123	1.188	1.076
1968	1.247	1.321	1.078
1969	1.206	1.209	1.021
1970	1.298	1.234	.967
1971	1.405	1.342	.967
1972	1.381	1.279	.941
1973	1.489	1.471	1.001
1974	1.356	1.347	1.011
1975	1.264	1.304	1.050
1976	1.539	1.625	1.075
1977	1.423	1.487	1.063

Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-9-76, May 1976, and Foreign Agriculture Circular FG-2-78, February 16, 1978.

The increase in the amount of land devoted to crops is apparent in the data shown in Table 2 for this sample of wheat-producing countries. The details would be different for other crops and other geographical samples, but the basic patterns are similar. Most of the increases in production of grain have come from increased yields. It is surely true that there will be additional land brought into production in future years, and this will be important; but it is probable that a large share of

future increase in production will come from increased yields as well. So the question of what has happened to yields over the past three decades is an important matter, because we need to understand how these past increases occurred if we are to be able to project future yields.

2.4 The controversy about yield trend

However, there are competent agriculturalists, economists and climatologists who do not agree that a plateau in grain yields has been reached. There will be continued advances in the application of scientific, technical and managerial knowledge that will result in increased yields, or in the increased effectiveness of storage, or in the greater efficiency of transport systems in future years. There are also exciting prospects for the development of new crops or cropping practices.

But there is also growing realization that some of the changes in the agricultural system that led to yield and production increases over the past three decades have also led to severe problems with soil erosion, loss of soil organic matter, and deterioration of soil condition. Competition for land for urban and industrial uses has taken productive land out of the agricultural system in many regions of the world.

Projections of future yield and production of grain that are just linear extensions of the trend that was observed in the past two or three decades are likely to be seriously in error if one or both of the following statements are true:

- (a) There is reasonable evidence that grain yields have reached a plateau, and that further major developments in the agricultural system will be required before the trend in yields will again be significantly positive.
- (b) There is reasonable evidence to support the hypothesis that a run of years with favourable crop weather coincided with some of the increases in yield that did occur during the 1950's and 1960's. A sample of such evidence has been presented by Haigh ^[2] and is shown in Figures 7 and 8. Haigh has estimated that about 15 per cent of the total increase in corn yield that was observed in the state of Illinois was due to a tendency for wetter and cooler weather during the peak of the corn growing season.

The most reliable projections of future grain yields and production will be based on a combination of projections of both future trend in the agricultural system and future climate. One hopeful sign that this is recognized as a worthy goal was a meeting of some fifty agriculturalists and climatologists at the University of Missouri in October of 1977. The published proceedings of the conference ^[3] should be a very useful reference for investigators who wish to see a careful review of work already done on the interaction of climate and agricultural technology.

If it is true that it will be some time before the application of scientific, technical, and managerial knowledge will again result in a trend toward significantly increased yields, and if it is also true that the climate for the next one or two decades probably will not be as favourable as that of the past two decades, then it will be more important than ever that serious attention be devoted to future projections of grain yield and production.

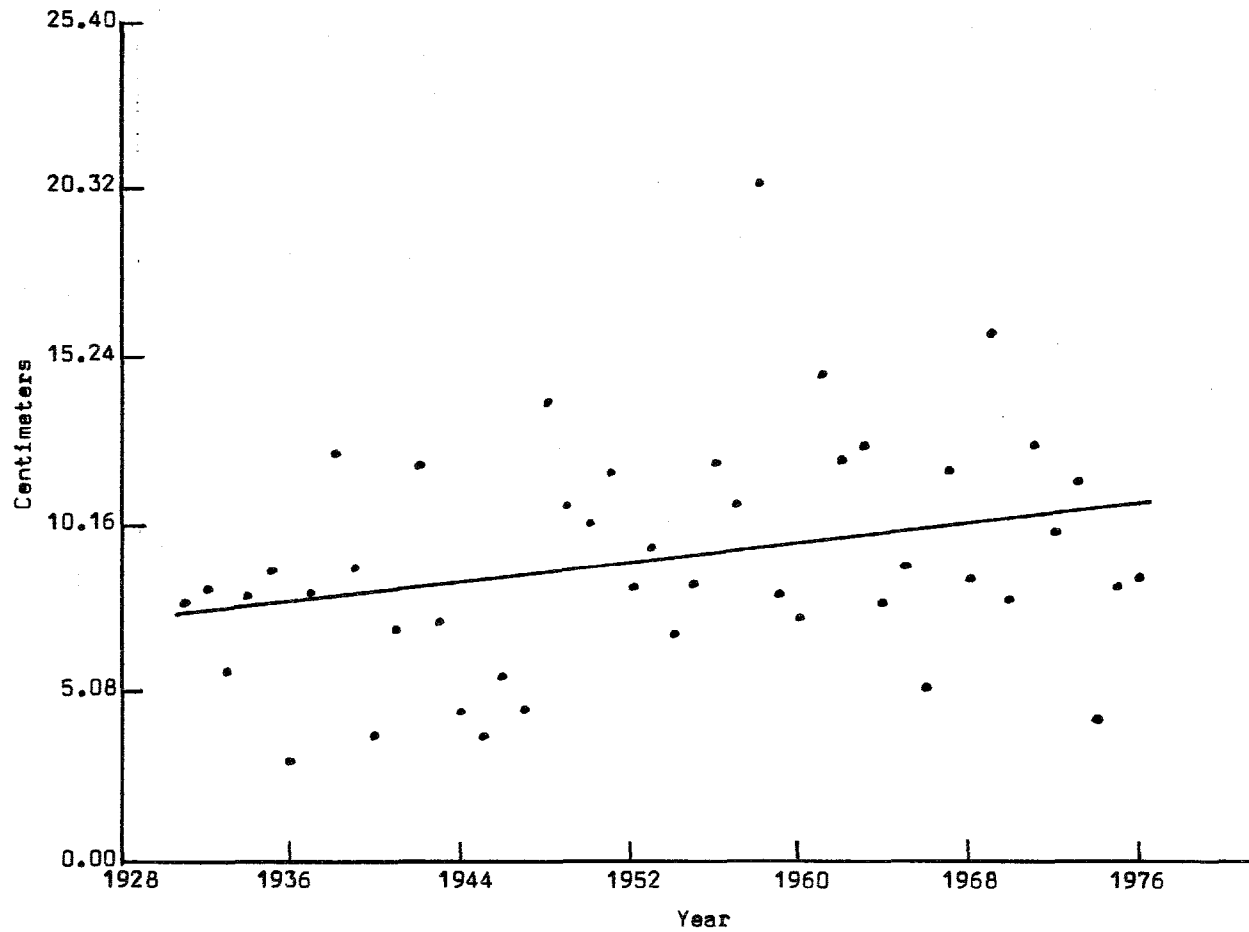


Figure 7. Illinois July precipitation. Source: Haigh, P.A. (1977). Separating the Effects of Weather and Management of Crop Production. Report to the Charles F. Kettering Foundation, 5335 Far Hills Avenue, Dayton, Ohio 45429.

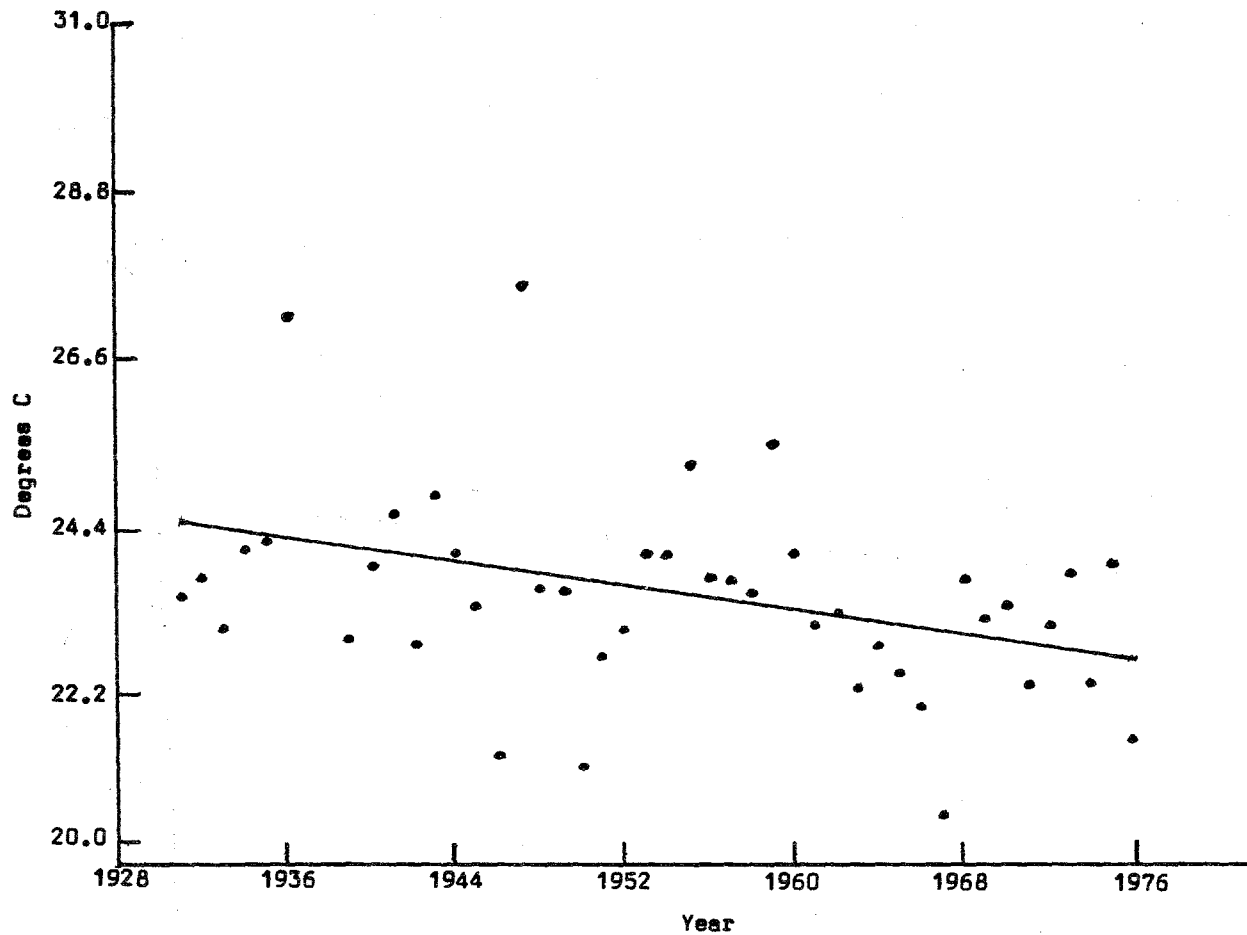


Figure 8. Illinois August temperature. Source: Haigh, P.A. (1977). Separating the Effects of Weather and Management of Crop Production. Report to the Charles F. Kettering Foundation, 5335 Far Hills Avenue, Dayton, Ohio 45429.

Beginning stocks as a percentage of utilization have varied from year to year, as shown for wheat and for all grains (wheat, coarse grains and rice) in Table 3.

Table 3

Beginning Stocks as a Percentage of Utilization

<u>Production Year</u>	<u>Wheat</u>	<u>All Grains</u>
1966	19	13
1967	28	16
1968	29	17
1969	34	19
1970	38	17
1971	21	13
1972	22	15
1973	17	11
1974	19	11
1975	18	10
1976	16	10
1977	24	14

Source: U.S. Department of Agriculture, Foreign Agriculture Circular FG-2-78, February 16, 1978.

The year-to-year variability in production, which can largely be attributed to year-to-year weather variability, can range from as little as 1 per cent of production to as much as 10 per cent. When beginning stocks get down to levels close to those reached between 1972 and 1976, the impact on grain prices is very strong and distribution of grain to shortage areas becomes very difficult.

In conclusion, the issue of future trend in grain yields and production is closely related both to future climate and to the future of the application of scientific, technical, and managerial knowledge.

3. Variability in crop season weather

Year-to-year variability in crop season weather is still a major cause of year-to-year variability in grain yield and production. This variability is the cause of much uncertainty in both the demand for grain and the availability of exportable grain. This uncertainty in turn results in the instability of grain prices and makes it difficult to manage the various important segments of the agricultural system.

In the long series of corn yield data from the United States that is shown in Figure 2, it is apparent that the yields over the period prior to the 1940's can be viewed as fluctuations above and below the mean for the period. Most of these

fluctuations were the result of year-to-year variability of crop season weather. Then, with the introduction of the complex mix of improvements in the agricultural system, there is a period of years beginning in 1950 and continuing through the decade of the 1960's when the deviations of yield around a trend toward higher values were comparatively small. It was during this period that many agriculturalists came to believe that they had witnessed the development of a crop management system that was less sensitive to the vagaries of weather. This is a fundamentally important issue, and it is not confined to the corn producing system of the United States.

If it were indeed true that a weather-proof agricultural system had been developed, then all of the concern about future climate that has been so widespread in recent years would be much ado about nothing. I share the belief of a number of agriculturalists and climatologists that the current grain-producing system of the world is still highly sensitive to the occurrence of large climatic anomalies.

There does seem to be evidence that grain yields have been subject to more variability from year to year in the current decade than they were in the previous two decades. Examples can be found in Figure 2 for United States corn yields, in Figure 3 for the national wheat yields for a number of temperate zone production regions, in Figure 4 for U.S.S.R. wheat yields and in Figure 5 for world total grains.

Haigh [2] has written, "The yields observed in a given year are a combination of climatic, economic and institutional factors. Crop carry-over levels influence government acreage set-aside programmes and therefore the number of acres planted. (This has been the case with the 1978 United States maize and wheat crops.) In years of high planted acreage marginal land will be used, making yields more susceptible to weather. Resource prices relative to expected crop prices influence not only planted acreage but also the resource mix adopted by the farmer, and therefore the technology applied to the crop. This also influences the sensitivity of yields to weather. The 1970's have seen an increase in planted acreage and an increase in relative resource prices, both of which will tend to increase the variability of yield, given weather conditions."

Haigh further argues that there are other forces at work in the agricultural system which seem to be working against a further decline in the impact of weather variability on grain yields. There appears to be evidence that modern monoculture practices have increased soil erosion and reduced the organic matter in the soil. Insects have become immune to some chemicals, while environmental concerns have led to prohibitions of the use of other chemicals, with the result that it is more difficult to control infestations. Costs of some agricultural inputs have increased to levels that make certain technological-managerial practices less attractive.

Then there is the further possibility that the year-to-year variability of crop weather has increased, compared to the variability observed during the 1950-1960 decade. Some interpret such a statement as a claim that there is a true climatic change in progress. I prefer to approach this question as a problem in sampling. What sample of previous years should be drawn to provide a statistical estimate of the variability of crop season weather for the coming one to two decades?

The two decades that saw most of the technological-scientific-managerial

changes in the agricultural production systems of the temperate zone countries (the 1950's and the 1960's) were also a period with relatively favourable crop weather from year to year. If the simultaneous occurrence of rapid technological development and favourable crop weather happened to be coincidence, then it is probably a mistake to assume that this will be the case in the coming decades. This assumption is even less attractive when a much longer period of record is used to estimate the year-to-year variability of yields, as was pointed out by McQuigg et al [4].

Haigh [2] used coefficient of variance analysis on a series of Iowa and Illinois corn yields and on a series of weather variables known to be strongly related to corn yields in those states. He used the first principal component on July temperature and precipitation in one section of his work and found that ... "The patterns of variability in Illinois and Iowa weather are quite similar, as would be expected. Both states show a decline in variability into the 1940's, a gradual increase into the late 1950's and a subsequent decline since the late 1950's. The decline in Iowa's weather variability was more pronounced than in Illinois. Combining these results to form the ratio of yield variability to weather variability, both states show a decline in relative variability into the mid-1950's with a slight tendency for yield variability relative to weather to increase since that time. Although this increase has been slight, this result is somewhat surprising in that it is often argued that technology is reducing the sensitivity of yields to weather.

Haigh's work on this problem has created a great deal of interest, but is not definitive since it was confined to the United States Corn Belt and the United States Great Plains Wheat Belt. Similar work should be done for crops in other major producing regions. But Haigh's results and a less sophisticated (but realistic) look at grain yields in the current decade both support the conclusion that the current grain producing system is still subject to the impact of year-to-year variability in crop season weather and that it probably will continue to be so throughout the coming decades.

4. Climate information systems

If it is true that agricultural yields have reached a plateau, then it will be more important than ever to generate and use information about future climate and to assess the impact of developing climatic anomalies. There are exciting developments in communications systems and in data processing and retrieval systems that can be adapted for use by farm managers, business executives, and policy level governmental officials. We are approaching the time when there will be few constraints on man's ability to generate, transmit and store virtually unlimited volumes of climatic, economic, agronomic and other kinds of management information. The challenge will be to make more effective use of this capability.

The discussions of the three preceding sections attempted to establish two basic concepts:

- (a) Agriculture should be defined in terms of a system that includes the activities that take place on farms and ranches together with the educational, business, governmental, and international activities providing agricultural inputs or support and facilities for marketing and distributing agricultural products.

- (b) Important changes have taken place in the agricultural system over the past three decades, leading to a trend toward higher yields and production of grain. There is some question whether a plateau has been reached in the response of the agricultural system. Projections of future grain yields and production must be based on a realistic assessment of the future impact of continued attempts to improve management, to develop technological-scientific inputs, and to adjust governmental policies.

However the future state of agricultural technology and management turns out, the agricultural system of the future will continue to be sensitive to year-to-year climatic variability 4,5, and also to longer term climatic change (though that is of less immediate concern).

Agriculturalists, business managers and government officials have a problem that can be stated as follows: "We have to project production and demand and estimate costs and income for our part of the agricultural system on a time scale well beyond the traditional day-to-day weather forecast. Meteorologists tell us that they are not yet able to forecast weather for a season or a year or several years in advance. What kind of information can be provided in order to help make projections within the agricultural system"?

I answer such questions in this fashion: "There are a number of kinds of information that meteorologists and climatologists can provide that can be used to help make such projections." Some types of information are:

- (a) For most of the productive agricultural regions of the world there are excellent long-term records of temperature and precipitation, covering from 50 to 150 years. In raw form, these data are not particularly useful. They can, however, be used to compute information about the statistical nature of weather events during some particularly important stage of crop development, in connexion with the design of structures or transport systems, or as input for a simulation model to assess the likely effectiveness of some new agricultural system. Then these long-term weather records are the potential source of much valuable management information.
- (b) The flow of current meteorological information from the network of surface and upper-air weather stations and from meteorological satellites can be used to provide an assessment of a meteorological situation that has already occurred, but which will have an impact on some part of the agricultural system in the future.

The past two winters in the United States Corn Belt provide examples of such use of meteorological information. The winter of 1976-1977 in this region was very dry and very cold. By late January and February, it was already apparent that the recharge of soil moisture that normally takes place during the winter would not be adequate. From the knowledge of what had happened and on the knowledge of the statistical probabilities, it was possible to issue statements that the 1977 crop season in the United States Corn Belt would begin with inadequate soil moisture reserves, that the 1977 crop season would probably begin with few difficulties with soil trafficability, and that the planting season would probably proceed earlier than usual.

The fall of 1977 and the winter months of early 1978 were comparatively wet and very cold. The subsoil moisture that had been depleted the previous crop season was replenished. Snow remained on the ground, and soil temperatures remained comparatively low as winter came to an end and spring got under way. As of late January and February 1978, it was possible to make some statements that were potentially very useful to managers of various components of the agricultural system. For one thing, it could be stated that subsoil moisture would not be a problem into the main part of the summer growing season. It was also possible to state that the 1978 growing season would probably get off to a late start. The application of anhydrous ammonia fertilizer, which is usually accomplished prior to the planting of corn, would proceed at a very slow pace.

These last two statements, made in early 1978, were useful to farmers, who were making last minute plans for the beginning of the growing season on their own land. The statements were also useful to managers of seed corn companies and fertilizer companies, to suppliers of fuel for farm machinery, and to officials of the United States Department of Agriculture. Early in the winter there had been some doubt about how many farmers would sign up for the acreage reserve programme. Later in the spring, as the planting season did indeed turn out to be later than usual, more farmers than had been expected signed up land that was still too wet for maize planting, putting it in the government acreage reserve, thus taking it out of production for 1978.

In addition to providing climate information for use in traditional agricultural activities, it is possible to generate information that can be used in new agricultural enterprises. Currently, there is much discussion of the possibility of introducing new crops. Some plant varieties that had traditionally been regarded as academic curiosities are now viewed as possible sources of energy through the production and use of biomass products. In many sub-humid regions, such as the United States Corn Belt, farmers are beginning to use large irrigation systems. There is no long-standing body of conventional wisdom concerning the management of these systems, as there has been for generations in some of the arid zone agricultural regions. Design of the water supply systems, choice of equipment type and size, and scheduling the day-to-day operation of irrigation equipment, in an agricultural region that is subject to considerable year-to-year variation in water need is creating a necessity for climate and weather information that did not exist a decade ago.

Most of the attention that has been devoted to agricultural climatology in the past has been concerned with the physical-biological interaction of plants with the atmosphere. Continued development of new crops, new methods of planting, cultivating, harvesting and storing the products of agriculture will surely require the best possible understanding of the impact of events in the atmosphere on these processes.

But with world grain reserves at lower levels and with the demand for grain increasing, there is a mounting concern with the impact of year-to-year climatic variability on grain prices and on the availability of exportable grain or on apparent surpluses of grain in some years. Individual farmers, farm cooperative groups, or governmental organizations have had to conduct their marketing or purchasing of farm products in recent years in the midst of increasing price volatility. Suppliers of the products and services needed by farmers (machinery, fuel, fertilizers and

chemicals) have had growing problems in recent years in anticipating large shifts in demand for what they have to sell and in anticipating what they in return will have to pay.

If it should turn out to be true that agricultural yields and production have reached a plateau, and if it should also turn out to be true that the climate of the next one or two decades will exhibit more year-to-year variability than was the case in the past two or three decades, then the difficulties that have been discussed in the preceding few paragraphs will not become any less severe.

At the same time that the need for better, more timely information about climate variability is increasing, we are in the midst of a major change in the capacity and speed of computer data processing and data communications systems, with significant reductions in the cost of those systems.

It may well be that the scientific-technological-managerial breakthrough of the coming decade in agriculture will not take place in the fields of biology or engineering but in improvements in the way management information about climate and the impact of climate can be made available. Along with this improved data handling capability will come significant improvements in the way information is used in the agricultural system as a whole.

5. A subject of widespread interest

The considerable interest in the assessment of the impact of climatic variability on crop yields and production as the season progresses has resulted in publication of many papers on the subject of weather and crop yields. This has been an item of interest for many years in the academic community. It is now a matter of applied science, with great practical value. A complete review of this literature is far beyond the scope of this paper. Baier 6,7 has assembled an excellent collection of such work by authors from many countries, including the work of Chirkov 8, Hashemi 9, Kulik 13, Ulanova 10, and de Wit 11.

The very large body of literature on pastoral agriculture is contained in the journals and publications of the biological, economic, agricultural engineering and agricultural meteorology disciplines. An illustrative sample of such work is by Maunder 14, Paltridge 15, Jones 12, and Roy and Peacock 16. Here again, the climate-related issues are the result of changing agricultural technology and substantial year-to-year climatic variability.

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CLIMATIC VARIABILITY AND AGRICULTURE

IN TROPICAL MOIST REGIONS

Hayao Fukui*

1. Climatic input required for assessing the impact of climatic changes on agriculture

This wide subject, climatic variability and agriculture is covered by three overview papers of this Conference, one concerned with temperate regions, another with semi-arid regions and the third, the present paper, with tropical moist regions. In order to aim at completeness, the discussion in this paper will deal with the entire region that is warmer and/or wetter than the temperate and semi-arid regions. The discussion will therefore not be restricted to the equatorial zone, where rainfall is plentiful throughout the year, but will also include, indeed with main emphasis, the climatic zone with a distinct dry period. The latter is the area of greatest population concentration whereas the equatorial zone is still only sparsely populated.

Among various climatic parameters, rainfall is of greatest concern to farmers in the humid tropics as a whole. It will be through change in rainfall that changes in a climatic regime have impact on agriculture in the humid tropics. Lower than average temperature may affect agricultural production in the tropical highlands and winter-season cropping in the sub-tropical zone. But this paper will touch upon only the probable impact of changes in rainfall on agriculture in the moist tropics.

In studies on long-term trends and periodicity of climatic parameters, various statistical methods have been used in order to smooth out year-to-year fluctuations. An example is an analysis of the trend and periodicity of rainfall in India from 1901 to 1960 [1]. The rainfall trend was upward in 13 out of a total of 31 climatic sub-divisions during the period, and the differences between the former and latter 30 years' mean annual precipitation in those 13 sub-divisions ranged from 4 to 19 per cent. Some periodicity was also recognized; 8.5 to 12.0 years in several and 2.0 to 3.5 years in more sub-divisions. The water level of lakes is sometimes used to study rainfall variability. In a study of Lake Victoria, possible periodicity with a period of over half a century is discussed [2]. It becomes increasingly difficult to make use of statistical methods for analysis of such a long-term periodicity because of the limited period of available data.

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The two examples mentioned above and many other studies, particularly those on the climatic history of the pre-instrumental era, demonstrate that the annual fluctuation of rainfall is not randomly distributed around a constant normal value, but that the latter varies. Therefore it may not be adequate to make any projections such as the premiums and indemnities for crop insurance on the basis of the means of climatic parameters for the past 30 years.

Existence of periodicity implies that wet and dry years may recur with a certain regularity. If short cycle periodicity such as the Quasi Biennial Oscillation (QBO) could be recognized with sufficient accuracy, it might help us forecast relevant climatic parameters a year ahead of time. Longer-term periodicity implies that wet or dry years tend to persist for a few years, or sometimes for decades. The damage of two consecutive drought years will be more than the arithmetic sum of the damage of two single years of drought which occurred separately. If periodicity with still a longer period, e.g. over half a century as suggested by the level of Lake Victoria, is proven to be really the case, "The climatic statistics of times before 1895 may be more relevant to the present day and for some decades ahead than the statistics of any period between 1900 and 1950" [2].

As mentioned earlier, the trend and long-term periodicity of rainfall become discernible only after year-to-year fluctuations are smoothed out and the result is shown in terms of a shift of the normal. This is the usual manner in which information on climatic change is handed over from meteorologists to agriculturists. In order to evaluate this climatic change from an agricultural point of view, however, it is not adequate to present it merely as a shift of the normal from, say, 1 200 to 1 100 mm.

Year-to-year variability is an inherent characteristic of climate. Therefore, adaptation of an agricultural system to a given climate is, more precisely, adaptation to a certain range of climatic parameters. In years or seasons during which climatic parameters remain within a tolerable range, agriculture is not seriously affected, while it will suffer serious setbacks in other years of anomalous climate. In other words, in a locality where the normal of the annual rainfall amount is 1 200 mm, agriculture there may not be affected seriously in any years with the annual total between 1 000 and 1 400 mm, which is within certain probability, say, in 90 out of 100 years. If so, it is more desirable for evaluating the impact of climatic change on agriculture to express the change not only in terms of the shift of normal from 1 200 to 1 100 mm but also in terms of the change in the expected range of rainfall in 90 out of every 100 years; for example, the range might change from that between 1 000 and 1 400 mm to that between 900 and 1 300 mm.

Before amplifying the above remarks, it should be explained that rainfall amounts often show a distribution that is far from normal or Gaussian, especially in arid zones or when periods shorter than a year or a season are analysed. However, let us assume that the annual rainfall amount has a Gaussian distribution with mean, \bar{x} , and variance, σ^2 . It is also assumed that agriculture is not adversely affected so long as the rainfall amount of any particular year is within the range of $(\bar{x} + k)$ (Figure 1a). Now, climatic changes involve changes in either \bar{x} or σ^2 or both. Therefore three types of climatic change are conceivable. In the first type, \bar{x} changes but σ^2 remains as before (Figure 1b). Since the agricultural system is well adapted

to the climate before the change and it usually takes many years, decades or perhaps centuries to adapt itself to the new climatic regime, the tolerable range, $(\bar{x} \pm k)$, does not change, at least immediately. The concomitant changes in probability that the agricultural system may suffer from anomalously deficient or excessive rainfall are shown by the areas marked with plus or minus signs in Figure 1. In the second type of climatic change, σ^2 changes but \bar{x} does not (Figure 1c). If σ^2 becomes larger than before, the increased risk of both deficient and excessive rainfall will result. Both \bar{x} and σ^2 change in the third type (Figure 1d). (See also Figure 1 of overview paper by Hare.)

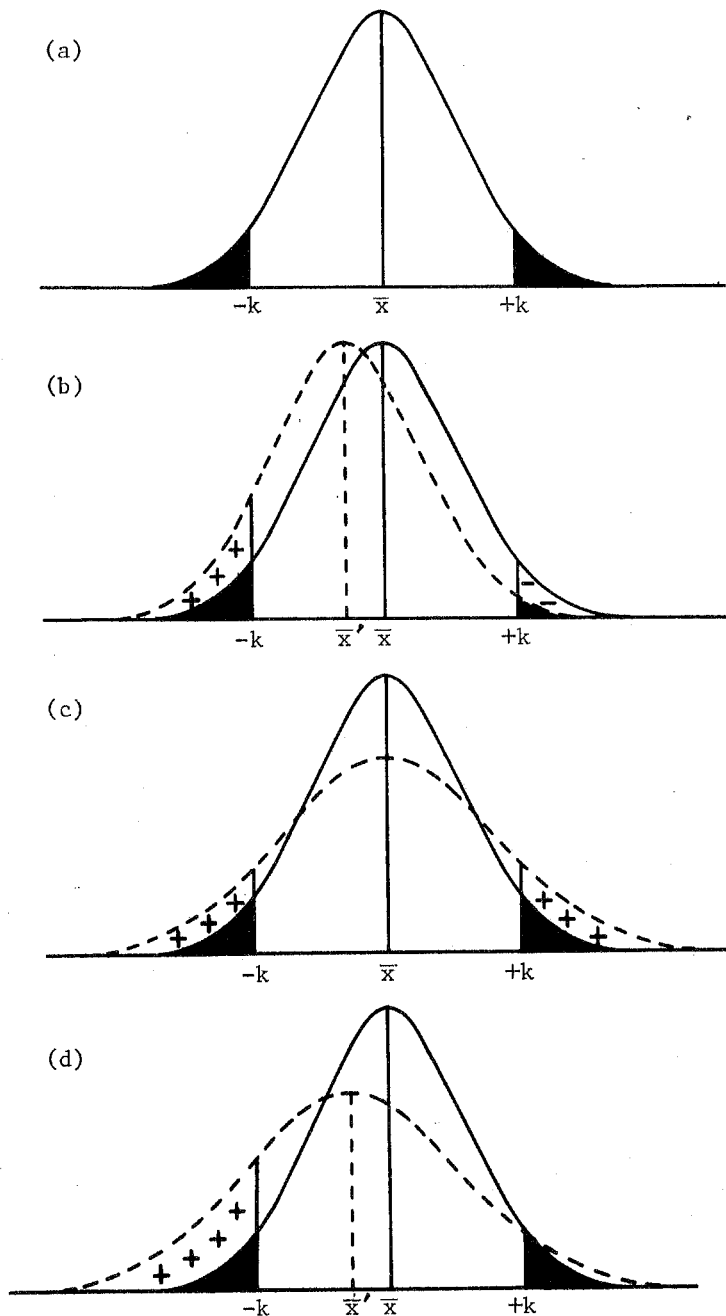


Figure 1. A schematic presentation of three types of climatic changes in relation to the vulnerability of agriculture

Thus, from the agricultural point of view, climatic changes should preferably be presented not only in terms of the shift of normals but also in terms of the changes in frequency distribution, that is, the changes in probability of occurrence of anomalies or of climatic parameters within a certain tolerable range. If only the shift of normals is indicated, its impact on agriculture could be assessed only when a certain relationship between the shift of normals and the changes in frequency distribution is assumed. Furthermore, the second type of climatic change in which only σ^2 changes but \bar{x} remains as before might not be detected if one pays attention only to the trend and periodicity of normals, although this type of climatic change might be of greater significance to agriculture than one with a small shift of \bar{x} without a change in σ^2 .

Studies of the long-term changes in frequency of anomalous rainfall in the humid tropics are very scarce. Three examples are introduced below.

Figure 2 shows occurrences of anomalously small and large amounts of seasonal rainfall in India based on the data of 22 stations with long period records. The Figure reveals that "the period between 1890 and 1919 was rich in both extremes, while the period 1920-1942 was quiet In the 1950's a high frequency of floods was accompanied by a low frequency of droughts; the reverse was true in the 1850's" [3]. Variance, σ^2 , appears to have become larger in the period 1890-1919 and smaller in 1920-1942 (the second type of climate change), while \bar{x} may have shifted to one direction in the 1950's and the other in the 1850's with or without change in σ^2 (the first or third type).

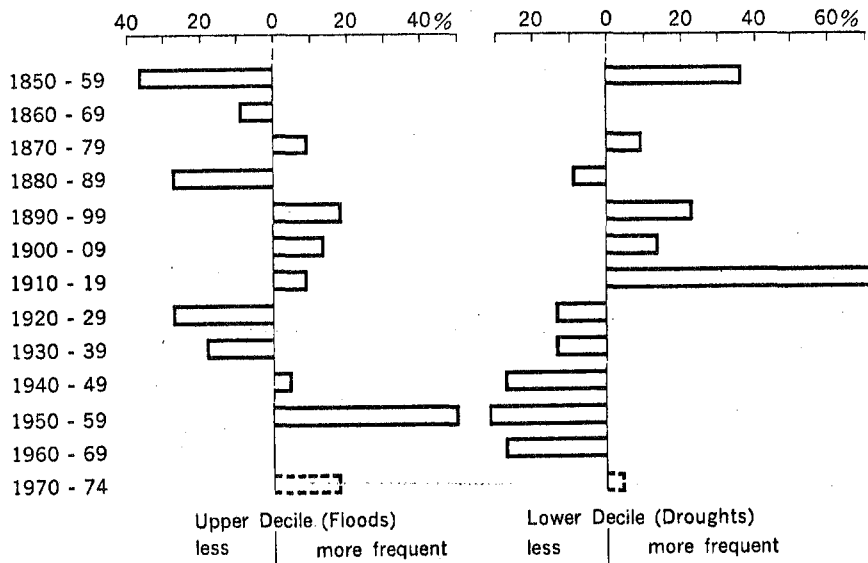


Figure 2. Extreme summer monsoon rainfall in India (22 stations), June-September. (Flohn, 1978. [3])

Yearly changes in the drought-affected acreage in India are shown in Figure 3. The authors concluded that "the country appears to be passing through a phase of great irregularities in the behaviour of the summer monsoon" [4]. Might this imply an increase of σ^2 , a shift of \bar{x} to the left hand side in Figure 1, or a change in both?

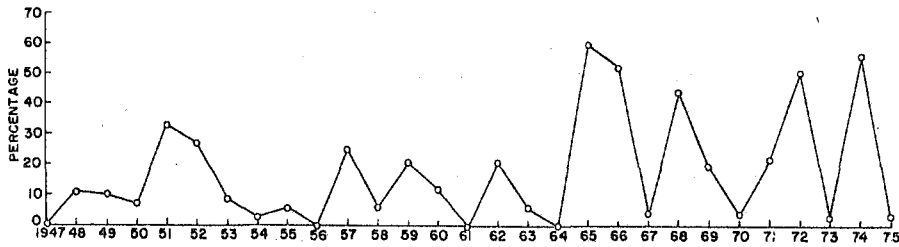


Figure 3. Percentage area of India over which summer monsoon seasonal rainfall is deficient/scanty during each of the years 1947-75. (Saha and Mooley, 1978, 4)

The third example takes up all of monsoon Asia, including the temperate and semi-arid zones. Based on the monthly rainfall data of 33 stations for the period of 1931-1974, the months with the amount of rainfall above or below the upper or lower quintile were first designated as anomalously wet or dry months, respectively. Second, the years during which four months or more were anomalously wet or dry were counted as anomalously wet or dry years. In Figure 4, the year-to-year changes in the number of stations which recorded anomalously wet or dry years are shown. One of the conclusions of this study is "that occurrence of both anomalously wet and anomalously dry years tends to be more frequent since the 1960's than before. We are now in the period of great variability of climate" 5.

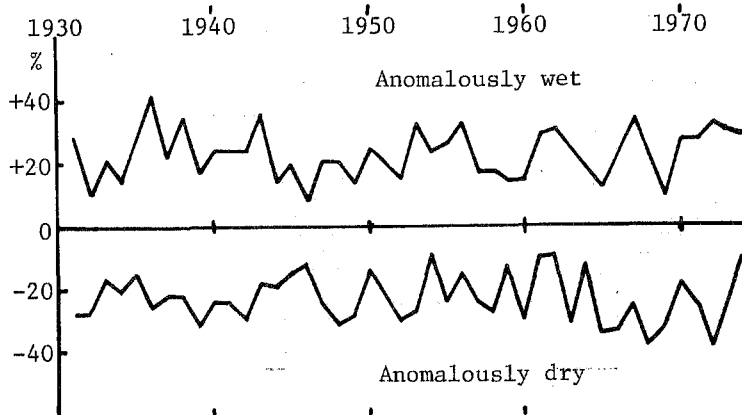


Figure 4. Year-to-year changes in percentages of stations recording anomalously wet or dry years in Monsoon Asia. (Mizukoshi, 1978, 5)

All the examples referred to so far deal with the trend, the periodicity or the changes in frequency of anomalies which are supposed to relate to some not yet well known natural phenomena. Apart from these climatic changes of natural origin,

the possibility of climatic changes due to human activities are being seriously considered. Whatever the causes of climatic changes, projection of the future is not yet at hand. This appears to be particularly so for the rainfall regime of the moist tropics.

However, the uncertainty of future climatic changes does not preclude the possible role of agricultural scientists in assessing their potential impact. As a first step to this end and, at the same time, as the first conclusion of this paper, I, an agronomist, want to emphasize the need for agricultural purposes, to present climatic changes in terms of the shift of normals as well as changes in frequency distribution. Once this climatic input becomes available, climatic changes can be expressed in terms of various secondary or derived parameters which have been proven to be of significant importance to agriculture.

2. The vulnerability of agriculture in the humid tropics to variable climate

2.1. Space and time variability

Once information on climatic changes is brought to agriculturists in terms of the shift of normals and changes in frequency distribution, it is the task of agricultural scientists to assess their impact on agriculture. The most powerful tool we can use to make this assessment is our knowledge of year-to-year variability of agricultural production, which is caused mainly by year-to-year fluctuations of climate. What happened in anomalous years in the past will tell us what will occur if a similar anomalous year recurs in the future, and what should be done in order to minimize its adverse effects. It is more difficult to imagine the impact of climatic anomalies that have never been experienced in the past.

However, it is not an easy matter to use past experience to assess probable future impact, primarily because agricultural systems vary widely according to region and to the time period. In other words, the k value in Figure 1 is not a constant. For instance, where crops are grown in the climatically marginal region (small k), even a minor climatic anomaly may affect them seriously, while the effect may not be so serious in a more favourably situated region (large k). To make things more complex, k changes from time to time. Changes in production technology, land use, farm economic status, etc. contribute toward the increase or decrease of the tolerable range of climatic variability. If we define the agricultural system in such a way as to include storage, transportation, marketing, processing etc., changes in the whole economic system of a society may affect the vulnerability of agriculture to climatic changes.

In these studies, discussed in Section 1, the criteria for anomaly appear to be more or less arbitrary: upper and lower deciles in the first example (Figure 2), equal to or less than 80 per cent of normal rainfall in the second (Figure 3), and upper and lower quintiles in the third example (Figure 4). Although these criteria might be meaningful from the meteorological point of view, their usefulness for agriculture must be examined carefully. Even if a criterion were proven to be meaningful to agriculture, it should always be kept in mind that its usefulness might be restricted to an agricultural system in a certain region at a certain time.

Thus, in order to assess the impact of climatic variability on agriculture, we require on the one hand, climatic input in adequate terms, and on the other hand, information on spatial and time variations in vulnerability of different agricultural systems. In other words, we need the expected values of all of \bar{x} , σ^2 , and k in Figure 1. If the expected change in k is relatively small, the magnitude of climatic changes will be the main factor in producing impacts. However, if the change in k is large, its new value will demand greater attention than the climatic changes.

2.2 Rainfall variability in tropical moist regions

At least 1 100 mm of annual precipitation is common in the humid tropics. Areas of such high rainfall are not so extensive in the temperate zone. Yet it is the variability of annual rainfall that is the main cause of year-to-year fluctuations in agricultural production in the humid tropics, too. It is often pointed out that the precipitation in the tropics is unreliable and that this is the reason for large annual fluctuations in agricultural production. But it is not a simple matter to compare rainfall variability in different regions because there seems to be no adequate measure of the relative variability of rainfall.

Biel's chart of world rainfall variability [6] is referred to very often even today. In this chart, variability is presented in terms of percentage departures from normal. The contrast between the arid and humid zones is sharply shown but the difference between the humid tropics and the humid temperate zone is not impressive. It may be interesting to compare the ways that two text books interpret this chart. In one, it is stated that:

"... in spite of much lower annual-rainfall totals, wide territories (of high latitudes) enjoy reliable precipitation, Certainly the rainfall of low latitudes is not more reliable on a per cent basis than that outside the tropics" [7].

The other says that:

"The humid tropics stand out as regions with a very low variability of rainfall. However, this picture is somewhat misleading, because the units of measurements, 1 per cent of the annual mean, are much larger in the humid areas than in dry zones" [8].

A commonly used measure of relative variability is the coefficient of variation or CV. But this is not always an adequate measure because CV is meaningful only when the frequency distribution is not far different from the Gaussian distribution. Nevertheless, CV is commonly used, partly because there seems to be no good alternative and, perhaps, partly because it can easily be computed.

An attempt was made to compare CV relative to mean values of monthly rainfall in the humid temperate and humid tropical zones. Data from 68 stations in the agriculturally important regions of the world for the period 1941-1970 were used. Only those months of over 50 mm mean monthly precipitation and not lower than 10 deg C mean monthly temperature were selected, which brought the total to 483 station-months. Figure 5a shows the relation between CV and means when all the data are considered,

while the data from 196 station-months in the humid tropics and 287 station-months in higher latitudes are shown in Figures 5b and 5c, respectively. The exponential curves are identical in all three figures. If rainfall variability in low latitudes differed significantly from that in high latitudes, the dots in the last two figures would be scattered on either side of the exponential curve. But, as we see, this is not the case at all. Therefore, rainfall variability does not seem to be greater in the humid tropics than in the temperate zone. However, we should note that the frequency distribution of monthly rainfall is usually quite far from the normal distribution, and it may be so even when months with over 50 mm rainfall are selected.

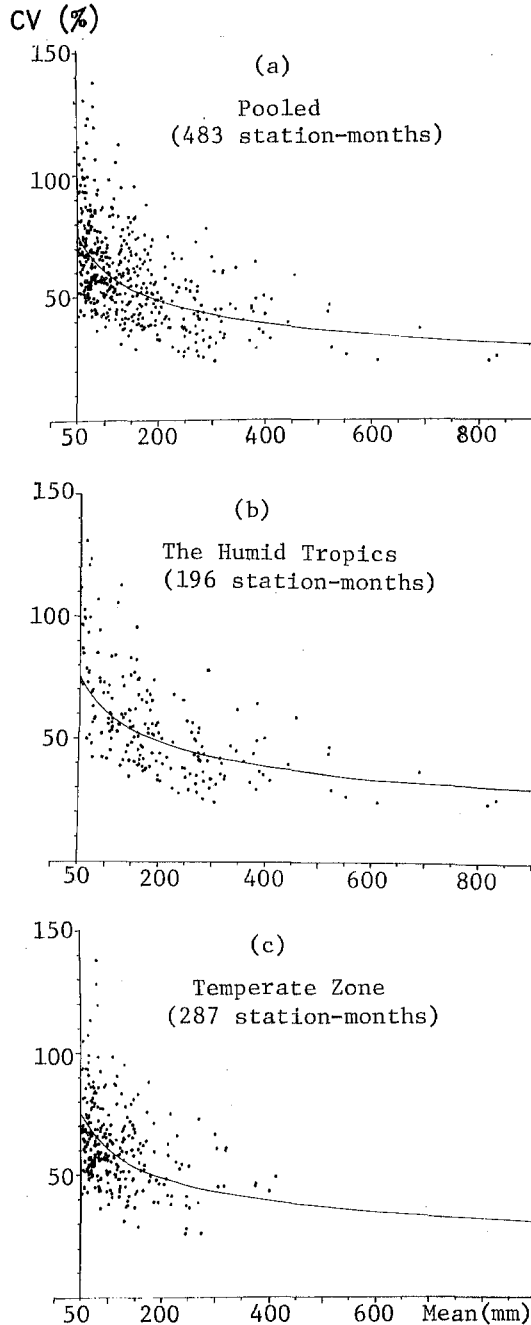


Figure 5. Comparison of relationship between coefficients of variation and means of monthly precipitation in the humid tropics and temperate zone.

When one deals with long-term annual rainfall records which usually show the Gaussian pattern, the curves of the cumulative probability diagram can be straightened by scaling the abscissa properly. The slopes of lines obtained in this fashion indicate variability of rainfall; flat slopes mean more reliable and steep ones less reliable rainfall. Figure 6 is an example on which Landsberg commented: "Particularly notable is the fact that the monsoonal zones have the greatest slope - a typical feast to famine pattern. It clearly shows the wisdom of the ancient hydraulic civilization of the region with water impoundment and irrigation" [9]. Perhaps it may be more meaningful to compare rainfall variability for each of the different climatic regions than to compare the whole region of the humid tropics with the whole region of temperate climate.

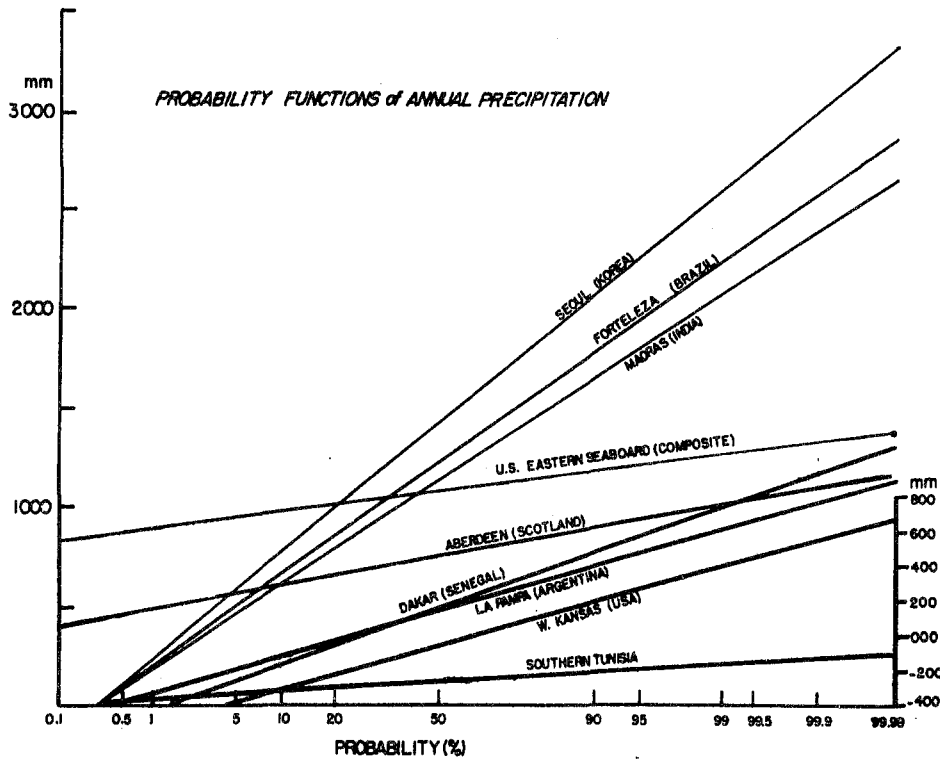


Figure 6. Probability function of annual precipitation amounts at selected localities in different climatic regimes (Landsberg, 1975, [9])

Differences between the amount of rainfall and the amount of water required are more directly related to agriculture than rainfall amount alone, since drought is a supply and demand phenomenon [10]. So far we have discussed only variability of the supply. The requirement for water varies widely according to kinds of crops, cultivation methods, soil conditions and many other factors. In dry lands, less moisture consuming crops are grown, while more demanding ones are grown in the humid areas. However, the moisture balance, assuming the most demanding crop, could serve as an index of the agricultural potential of regions in terms of moisture availability. Or it will affect the range of choice of crops as far as moisture is concerned. The amount of water required by the most demanding crop could be estimated by the amount of potential evapotranspiration (PET).

In view of this, differences between precipitation (P) and potential evapotranspiration, (P-PET), were calculated on a monthly basis for 20 stations, ten each in the humid tropics and temperate zone, for each year during the period 1941-1970. PET was estimated by Thornthwaite's formulae but soil moisture retention, moisture carried over from preceding months, run-off etc. were not taken into account. Figure 7 shows the means and lower quintiles of P and P-PET. Note that except for the three stations in the equatorial climate, the apparently great advantage of the humid tropics over the temperate zone when judged only from rainfall amounts (Figure 7a) nearly disappears when we look at the balance (Figure 7b).

In the temperate region, some stations have rather dry or wet winters, but in comparison to the tropics, the precipitation is rather evenly distributed over 12 months, except for Salisbury where winter has virtually no rain. Regardless whether the winters were wet or dry, however, the moisture balance was positive in this season, even in the sixth driest year during 30 years. Even if there is no crop in the fields, or growth is retarded during winter, water stored in the soil during this period makes a substantial contribution to the vigorous growth of crops at later stages. In spring and early summer, it becomes progressively drier but the balance remains not less than -50 mm until the driest period when it falls below that level for two to three months at most. This picture looks ideal for the growth and maturation of annual grain crops.

In most parts of the humid tropics, the seasonal variation of rainfall is immense. Some examples show the unimodal and the others the bimodal pattern. Except for the equatorial climate region, the dry period is long and severe, especially in the monsoon climate. The growing season of annual crops is restricted to the rainy period. Unlike the situation in the temperate zone, the pre-season storage of soil moisture is negligible. Therefore, annual crops must depend totally on the rainfall during the growing season. In many places, there are only a few months with positive moisture balance. On average, in one out of every five years, there are no or one such months.

It is often said that the daily and hourly maximum of the tropical rainfall is great, and this characteristic reduces the ratio of that part of rainfall which is actually absorbed by crops to the total rainfall amount. Tropical soils, particularly those coarsely grained ones derived from old terrace and plateau materials, are very poor in water-holding capacity. These and other factors will make the water balance in the humid tropics even less advantageous than that shown in Figure 7b.

From the discussion above, it can be concluded that:

- (a) rainfall reliability is not necessarily less in the humid tropics as a whole than in the humid temperate zone, though it may be so in areas of monsoon climate;
- (b) it may not be correct, therefore, to say that large year-to-year fluctuations in agricultural production in the humid tropics in spite of much greater mean rainfall amounts is primarily due to greater variability of rainfall;

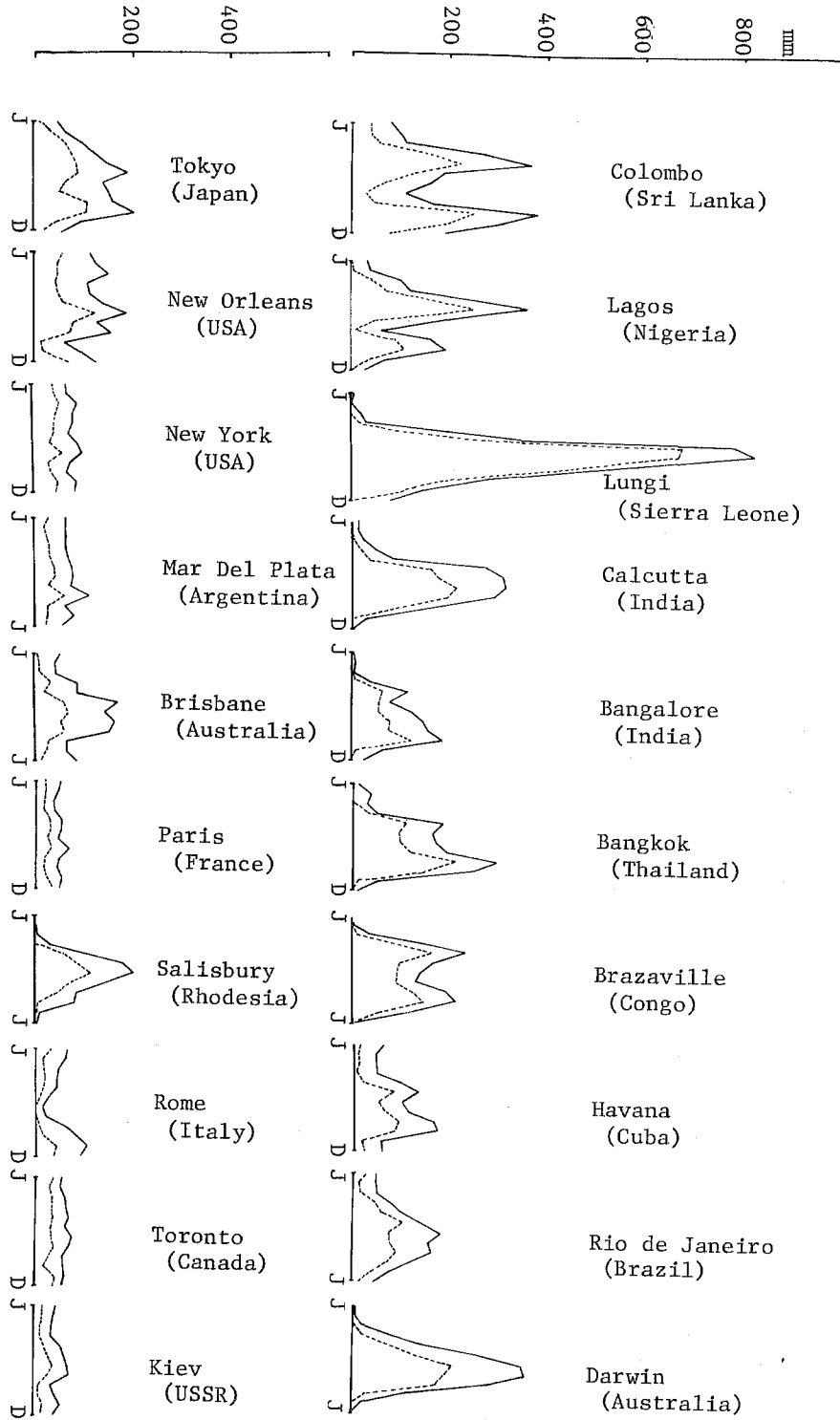


Figure 7a. Means (solid lines) and lower quintiles (dotted lines) of monthly precipitation at 20 stations

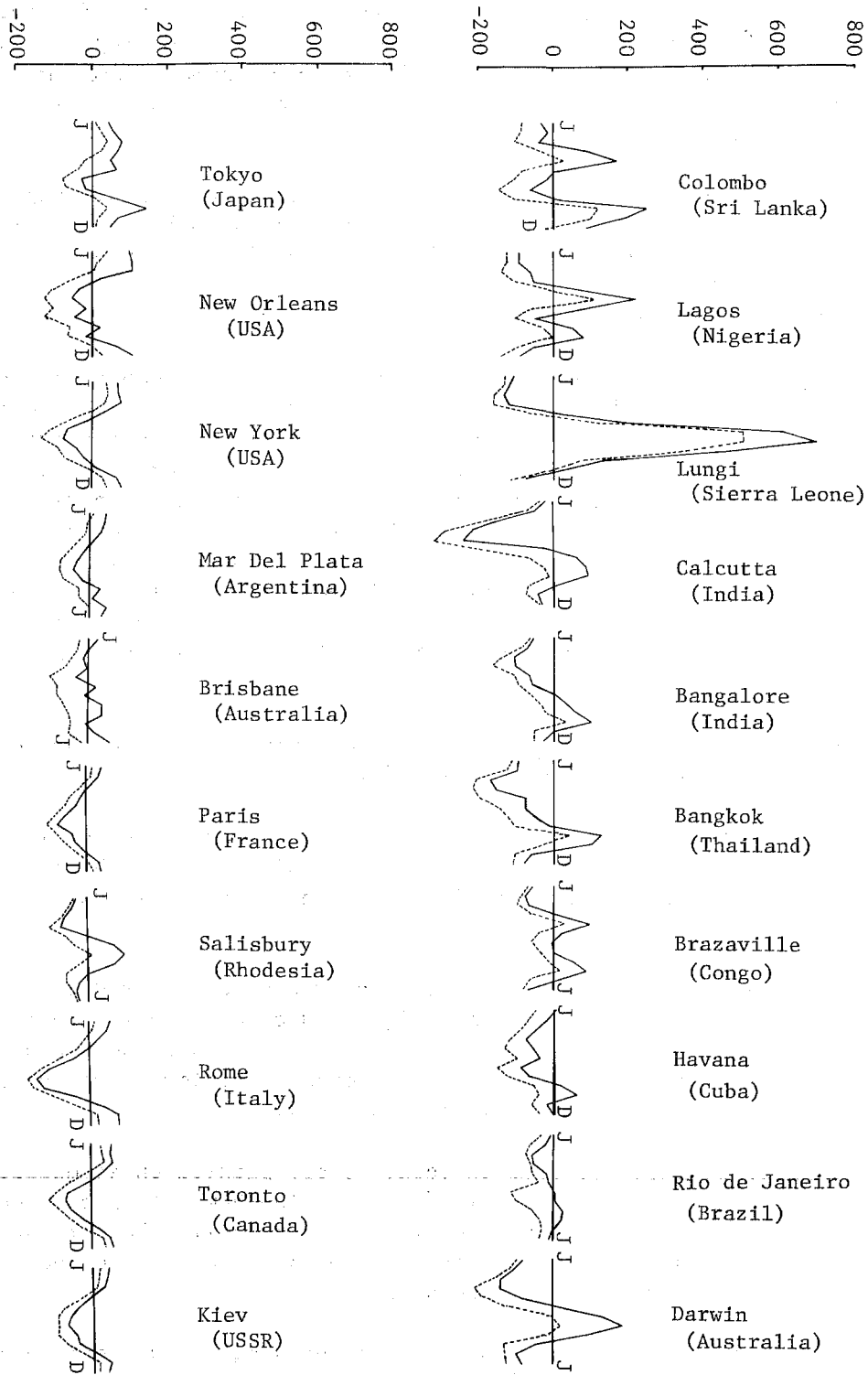


Figure 7b. Means (solid lines) and lower quintiles (dotted lines) of monthly differences between precipitation and potential evapotranspiration (P-PET) at 20 stations

- (c) in terms of water balance, the humid tropics have no advantage over higher latitudes, and the major part of the humid tropics, i.e. regions with a distinct dry season, is hydrologically marginal when the seasonal pattern of rainfall is considered in relation to suitability for annual crops, and thus
- (d) unstable agricultural production, especially of annual crops in some parts of the humid tropics, is due basically to hydrological marginality of the region rather than to large but variable rainfall.

2.3. Vulnerability of different crops to rainfall variability

In Figure 8, the delimitation of the humid tropics is approximated to international boundaries, or state borders in the case of Brazil and India, because in these two countries there are substantial areas which are not really in the humid tropical climatic zone. By such an approximation it is possible to enumerate agricultural statistics. In Table 1, the composition of crops on arable land in the humid tropics is compared with that in the rest of the world. As we see, cultivation of annual crops other than rice, particularly of upland grain crops, is the norm of agriculture outside the humid tropics, while other types of agriculture are also of great significance in the humid tropics. This is especially so in the Asian and Oceanic humid tropics, which contain about two thirds of the total arable land area in this climatic zone.

The relative significance of annuals other than rice in the humid tropics is further reduced when one takes account of the following points:

- (a) A substantial area within the humid tropics as shown in Figure 8 is not actually of typical humid tropical climate, notably the dry zone of Upper Burma, part of the Deccan Plateau of India, part of Sahel of West Africa, etc.
- (b) The relative importance of the crop groups is compared in terms of harvested acreage in Table 1, but significance of annuals other than rice in the humid tropics is much less in terms of production because they are grown by the shifting cultivation method in a large area and, hence, the average yields per unit area are low.
- (c) Tree crops (not included in Table 1) are planted on 44 million ha or two per cent of the total land area in the humid tropics, including the whole territories of Brazil and India, while the corresponding figures for zones outside the humid tropics are 35 million ha or 0.3 per cent. (FAO Production Yearbook 1975)

Due attention should be paid to the fast leaching of nutrients and the great risk of erosion in humid tropical agriculture. This is especially so when a short-term upland crop is cultivated, since the cultivation of these crops leaves soil temporarily uncovered every year. Not only the risks of land deterioration but also the direct influence of climatic conditions on these crops' physiology make their cultivation in the humid tropics unfavourable. For instance, temperatures may be too high

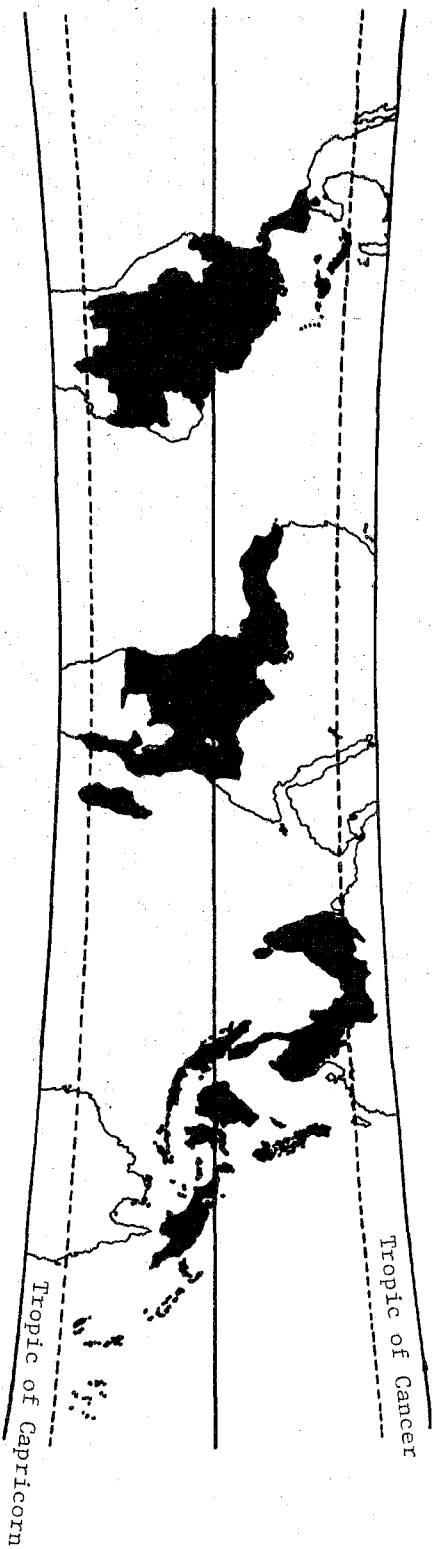


Figure 8. Map showing the countries of "The Humid Tropics".
(Note: The climatic delimitation of the humid tropics is approximated by international boundaries. For Brazil and India, state boundaries are used.)

Table 1

Harvested area of different crops in "The Humid Tropics"¹⁾

	Annual flowering crops other than rice ²⁾	Rice	Short-term vegetative crops ³⁾	Total
Africa	37 (67) ⁴⁾	4 (7) ⁴⁾	14 (25) ⁴⁾	55 (100) ⁴⁾
Americas	10 (50)	5 (25)	5 (25)	20 (100)
Asia and Oceania	75 (50)	66 (44)	10 (7)	151 (100)
"Humid Tropics," total	122 (54)	74 (33)	29 (13)	226 (100)
Rest of the world	670 (86)	63 (8)	43 (6)	775 (100)

1) "Humid Tropics" as defined in the text and shown in Figure 8.

2) Cereals other than rice, pulses, oil seeds, and cotton.

3) Roots and tubers, sugarcanes, and fibre crops.

4) Percentage of each of three crop-groups, assuming their sum to be 100 %.

These crops account for approximately 80 % of the total arable land.

(Data source: FAO Production Yearbook 1974.)

for some crops, or severe damage or even total failure of annual crops may occur when certain critical growth stages such as flowering and fertilizing periods coincide with very strong rain in a very short period or with the strong winds of typhoons, cyclones or hurricanes. Hydrological marginality and the accompanying high risk of water deficiency as discussed in the foregoing sub-section are also factors discouraging the cultivation of these crops. By contrast, lowland rice and vegetative crops are, in general, better adapted to the soil and climatic conditions of the humid tropics.

Various risks and uncertainties appear to discourage the cultivation of annual crops other than rice in the humid tropics. However, Table 1 shows that in 1974, more than half of the total arable land was used for annual crops. Furthermore, changes in crop composition between the years 1954 and 1976 indicate that the relative importance of upland annuals tended to increase (Table 2). Does this imply that the vulnerability to climatic variability of humid tropical agriculture as a whole is increasing, that is, that the k value is becoming smaller?

As mentioned earlier, a substantial portion of the acreage planted in annual crops other than rice is under the shifting or slash-and-burn cultivation system. This system is one of the examples of adaptation of indigenous agriculture to environment, because the risk of land deterioration can be minimized by this method. However this risk is minimized only when population density falls below a certain level. If density exceeds that level, the fallow period becomes shorter, lowering the yield per unit area. The poorer yield necessitates the burning of a larger area, which, in turn, results in a still shorter fallow period. This vicious circle ultimately produces infertile land which cannot be used anymore. It is said that the core area of the ancient Maya civilization was relocated because of this problem. There are many similar examples in the present day humid tropics. The vast expansion of infertile land, often covered with Imperata spp., suggests the extent of this man-made disaster.

The primary cause of overpopulation in the region of shifting cultivation is the explosive population increase in the last few decades. Besides that, however, population concentration in a certain area for other reasons aggravates the situation.

If shifting cultivation is to be practised without causing irreversible deterioration of land, a long fallow period must be guaranteed, which means that a small group of cultivators must command a large territory and, hence, groups have to live sparsely scattered over a large area. Such a settlement pattern is detrimental to national unity and modernization. Therefore, various schemes for resettling shifting cultivators have been initiated, but many of them have simply resulted in land deterioration and an eventual shift on an even larger scale as long as the basic method of cultivation was unchanged.

Apart from these forced or planned resettlement schemes, the spontaneous movement of population sometimes causes overpopulation in a certain area. Such movements are often motivated by better chances for education, medical care and use of other modern facilities, as well as opportunities to get additional cash income. In some places, better political security may be a strong motivation. Thus, the development and modernization of the countries in the humid tropics seem to make the life of the shifting cultivators in remote areas less and less attractive than before. Such socio-economic and political factors are more important reasons for overpopulation than are changes in the population-land ratio of a whole country.

Table 2

Changes in short-term crops' acreage in the humid tropics¹⁾
during 1954-76

		Annual flowering crops other than rice ²⁾	Rice	Short-term vegetative crops ³⁾	Total
(million hectares)					
Africa	1954	16.9 (70) ⁴⁾	1.7 (7) ⁴⁾	5.4 (23) ⁴⁾	23.9 (100) ⁴⁾
	1976	31.2 (77)	2.8 (7)	6.6 (16)	40.5 (100)
America	1954	15.5 (65)	3.0 (13)	5.5 (23)	24.0 (100)
	1976	34.8 (68)	8.0 (16)	8.6 (17)	51.4 (100)
Asia and Oceania	1954	6.6 (23)	20.4 (69)	2.4 (8)	29.5 (100)
	1976	12.5 (28)	27.3 (61)	4.8 (11)	44.6 (100)
"Humid Tropics"	1954	39.0 (50)	25.1 (32)	13.3 (17)	77.4 (100)
	1976	78.0 (57)	38.1 (28)	20.0 (15)	136.6 (100)

-442-

1) The area of "the humid tropics" is basically the same as in Table 1. But the comparable figures for 1954 and 1974 are not available for some countries and territories, particularly in Africa. In Asia, the whole of India was deleted because the state-wise crop statistics for each state for 1954 were not on hand. All of Brazil was included, though more than half of its arable land is not in the humid tropical zone.

2) Cereals other than rice, pulses, oil seeds, and cotton.

3) Roots and tubers, sugarcanes, and fibre crops.

4) Percentage of each of three crop-groups, assuming their sum to be 100 %.

(Data Source : FAO Production Yearbooks)

This discussion leads to the following conclusions:

- (a) Only if we accept the condition in which a large proportion of a country's population remains scattered in remote areas and can neither benefit from nor participate in the nation's development and modernization, can shifting cultivation be practised without irreversible deterioration of land assets.
- (b) However, this is not realistic in the long run. Therefore, the method of cultivation should be altered, since the shifting cultivation method seems to be incompatible with the concentration of population in a limited area, an apparently necessary condition for modernization.

What sort of cultivation system or systems should replace the shifting cultivation method? Could sedentary cultivation of upland grain crops be an adequate form of agriculture? The fact that increasingly shorter fallow periods eventually force farmers to abandon their land suggests great difficulty for sedentary agriculture in the humid tropics. However, modern fertilizer and soil conservation technologies might be able to overcome this difficulty. Although such technologies certainly exist, a more important consideration is whether they could be used by the majority of poor peasants, given the necessary inputs.

It is said that shifting cultivation was practised widely in the now developed countries in the temperate zone some time ago, when there was no shortage of cultivable land. But population increase and concomitant land scarcity necessitated the utilization of advancing technology to develop methods to use the land more intensively. To some extent, this could be applied to the humid tropics, but it should be noted that the sedentary cultivation of upland grain crops in the humid tropics has not supported any big concentrations of population. The course of agricultural evolution in the temperate zone may not be repeated in the humid tropics. There are ample reasons for this from the agro-environmental point of view.

The second type of cultivation of annual crops other than rice in the humid tropics is the continuing cultivation of these crops on the same plot of land year after year; much of the produce is simply eaten by the cultivators. In Asia, rice is almost always preferred as a staple food, but where land suitable for lowland rice cultivation is unavailable, maize, sorghum, upland rice, cassava, peas and beans, etc. are grown primarily for direct consumption. In those Asian countries where per capita consumption of rice is low (less than 100 to 150 kg per person per annum), these crops are major sources of food for a substantial proportion of the total population.

In these countries, the villages depending on upland crops for subsistence are normally newer than the rice growing villages in the lowlands. This means that the scarcity of suitable land for lowland rice cultivation pushed less fortunate peasants from fertile valley bottoms to dry uplands. Their dietary habits are not necessarily due to their preference for upland crops. Therefore, their consumption of rice increases when either its price becomes lower or their income increases. It is said that the sudden drop in rice exports from Burma was partly due to the Government's policy of distributing cheap rice to hitherto non-rice eaters in remote mountain areas.

Thus, the second type of upland crop cultivation will not persist if enough rice is produced to feed the whole population, or if extra income from other sources enables the cultivators of these crops to purchase rice. But unfortunately it is unlikely that this will happen in the near future. Instead, this type of cultivation will most probably continue to increase. Thus more and more marginal areas will be used by this type of agriculture which may prove to be the form of humid tropical agriculture most sensitive to climatic variability.

The third type of upland crop cultivation in the humid tropics consists of feed crops primarily for the export market. This is a recent development and should be examined carefully. The most notable examples are soybeans in Brazil (Figure 9) and maize and sorghum in Thailand (Figure 10). These crops are grown commercially. Though Thai maize is grown by small farmers, their staple food is rice. The demand for these crops is and will continue to be great because of increasing consumption of animal rather than vegetable food and the concomitant increase in calorie intake towards that of higher income countries. As long as these crops can be exported at a price level equal to or lower than the Chicago quotation, there will be no difficulty in finding buyers.

The traditional agricultural commodities exported from the humid tropical countries are coffee, cocoa, tea, coconuts, bananas, sugar, jute, rubber etc., and more recently oil palm. All of these are either perennial crops or vegetative crops. The demand for these crops cannot be expected to increase dramatically in the near future. It will be very difficult for newcomers to compete against traditional exporters of these products. Conversely, the export of feed crops is quite a new affair. It opened a new way to earn foreign currencies, which are badly needed by developing countries. Thailand and Brazil are the forerunners who first realized this possibility. But can this be called a success story?

The production of maize in Thailand was very much affected by the weather in 1972. Figure 10 shows the monthly rainfall at three stations in the major maize growing areas. Maize is grown during the early part of the monsoon season, i.e., April to August. In 1972, rain was very scanty in May but normal in June. In July and August it was also less than normal in some places. Cassava is another Thai export crop; its acreage has been increasing at a great rate in the last decade. The cassava growing area is not so far from the maize area and some sections overlap. At three stations in the cassava area, rainfall was as scanty as in the maize area in May, July and August of 1972. But the cassava production seems to have been hardly affected (Figure 11). As the above example demonstrates very well, annuals are very susceptible to short term water stress, while root crops are quite resistant to it.

In shifting cultivation various crops are planted after burning, and the cultivation may continue thereafter for one or more years. In the first year, the most demanding crops are grown, and less demanding ones are planted in the following years. Often the last crop planted is cassava. In West Africa, it is reported that the gradual deterioration of the soil under sedentary agriculture makes it difficult to grow maize and yams, and, in their place, cassava is planted in large areas. In Thailand, maize planters are exploiting new lands, while old and less fertile maize fields are now either planted in less demanding crops such as sorghum and cassava or totally abandoned.

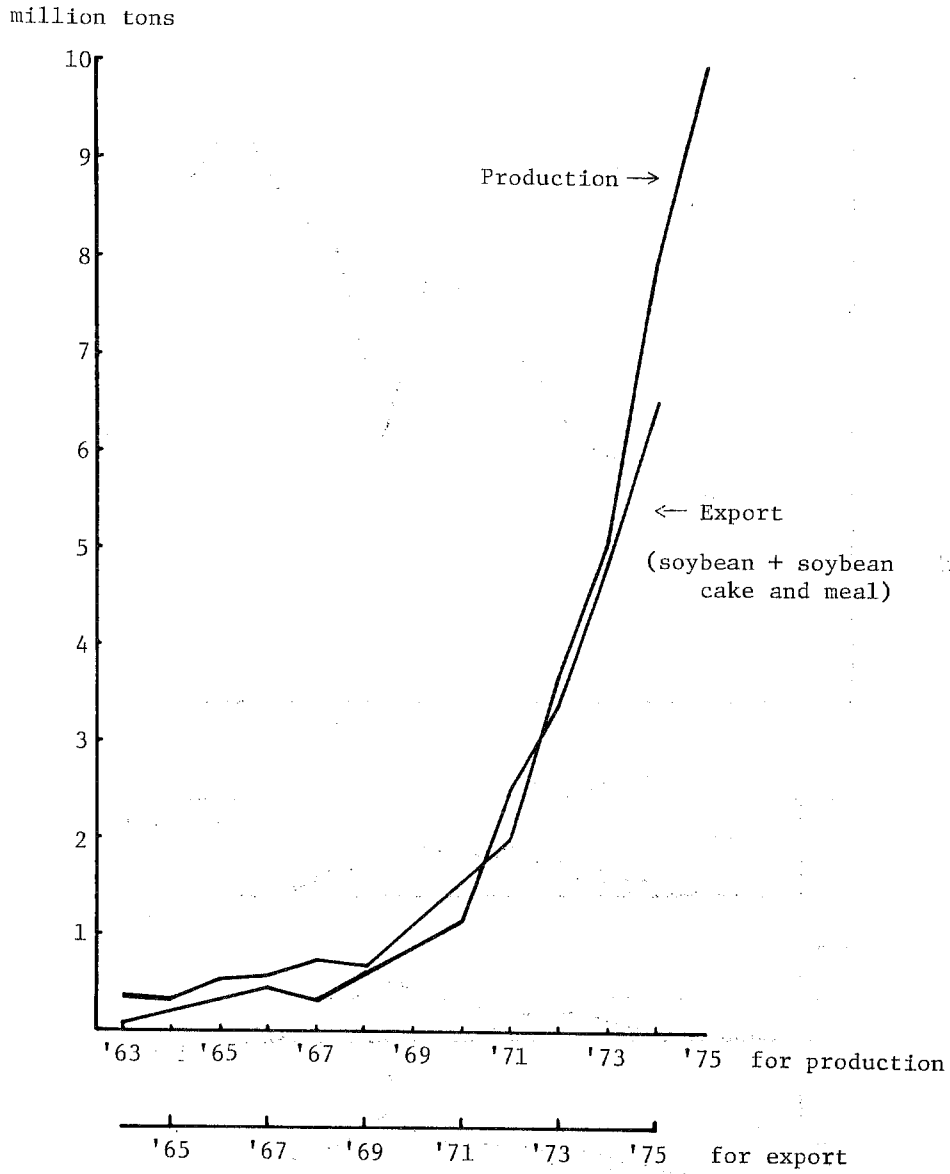


Figure 9. Brazil's production and export of soybeans, 1963-1975. (Source: FAO production yearbooks and trade yearbooks.)

million tons

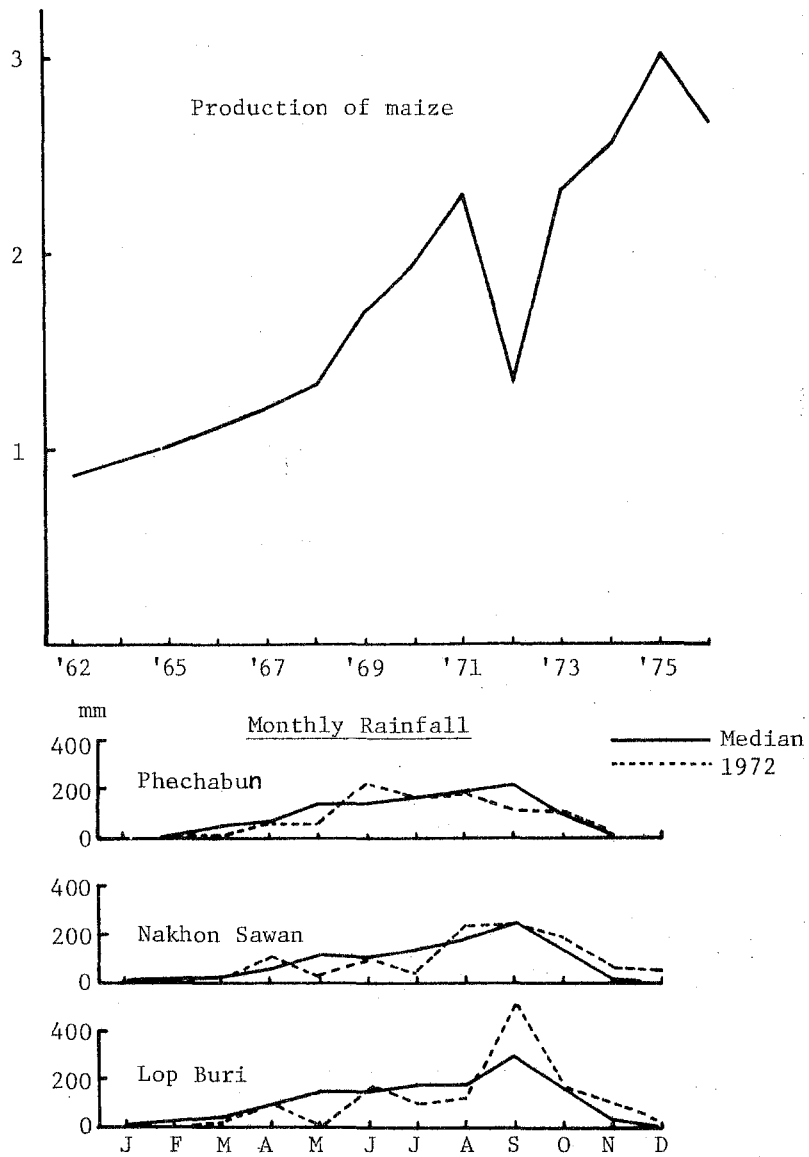


Figure 10. Rainfall and production of maize in Thailand in 1972.

million tons (fresh root)

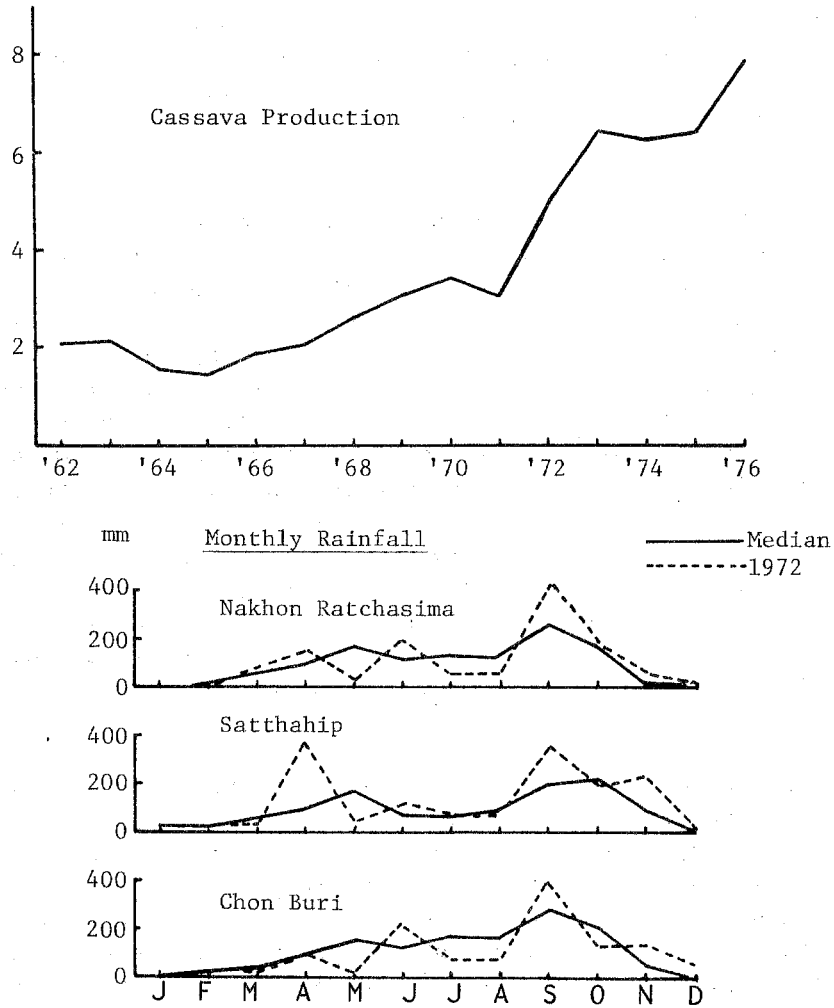


Figure 11. Rainfall and cassava production in Thailand in 1972

One of the characteristics of the genesis of residual soils in the humid tropics is that differences in parent material are very strongly reflected in soil formation. Most of the residual soils of reasonable fertility and resistance to erosion in the humid tropics are formed in areas of neutral to basic rocks such as limestone, basalt and basic volcanic ejecta. The sedentary cultivation of upland crops in the humid tropics is mainly distributed in these soil areas. It may be feasible to maintain the fertility level and prevent erosion of these kinds of soil and the sedentary cultivation of upland grain crops might be possible on a sustained basis.

The Mekong Committee has proposed a long-term land use plan for the Lower Mekong Basin (Figure 12). As we see, areas suitable for three major kinds of land use are delineated on the map. The first are the areas principally suitable for paddy fields, where different kinds of water control devices enable the mono-culture of rice or rice-based multicropping systems. The second, mainly in the mountains, are the areas designated as nature reserves. The third areas are those in which rain-fed upland crop agriculture should be feasible. The third areas are regions whose soils are derived from neutral or basic rocks and riverine levee material. The remaining vast area for which no land use designation has been proposed may be topographically suited to agriculture, but either inferior soil conditions make it inadvisable to cultivate upland crops on a sustained basis or poor hydrological conditions make cultivation of lowland rice difficult. At present these inferior areas are being exploited either by planters of kenaf or cassava or by rice growers, and the rest is covered with very poor stands of deciduous forest. Rice cultivation in such areas is extremely unstable: in some places farmers are fortunate if they can plant rice in one out of five years.

Three types of cultivation of short-term upland crops in the humid tropics have been discussed above. In all cases, there are strong reasons to continue or even to expand such risky types of cultivation. However, technology to prevent land from deterioration may be known, but various social, economic and cultural factors make its application difficult. Therefore, these types of cultivation are likely to expand to more marginal regions without proper measures to prevent land deterioration. This implies that vulnerability to climatic variation will not diminish but may increase in the foreseeable future.

What can be done to prevent land deterioration? It is evident that greater efforts should be directed toward research in and dissemination of suitable technology to achieve such an end. However, it might be unrealistic to expect the development of prosperous rural communities based on the sustained cultivation of short-term upland crops and taking adequate measures to prevent land deterioration. Hence, any efforts to make such conditions possible might not be rewarded except in rather limited areas of suitable soils. It appears, therefore, that this kind of agriculture should be totally replaced by other systems which have already been proven to be better adapted to the humid tropics, i.e. cultivation of lowland rice and other crops on paddy lands and/or perennial crops on upland.

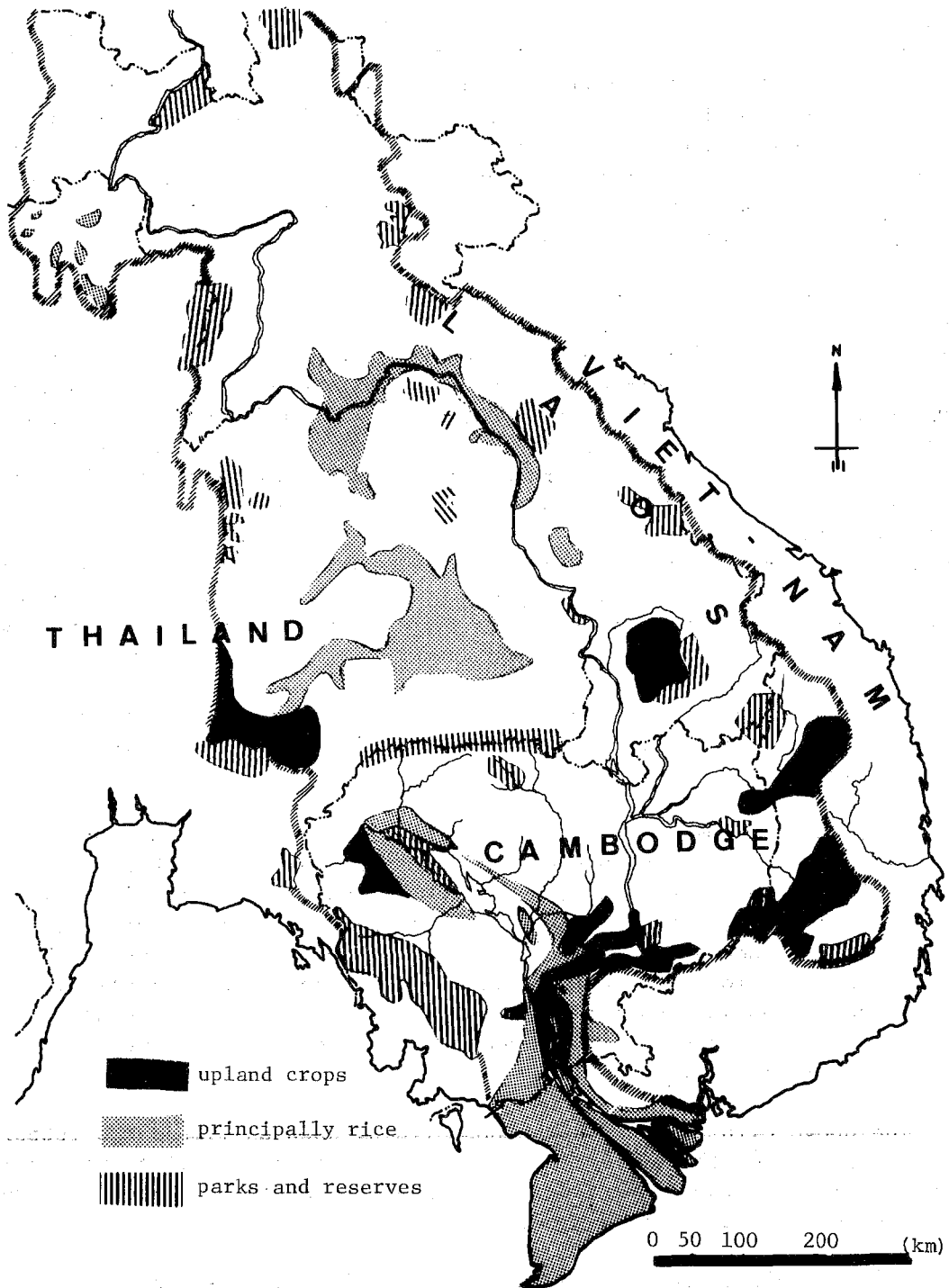


Figure 12. Tentative land use model for the lower Mekong Basin (simplified)
(Source: Mekong Committee, 1976.)

At present in the Mediterranean region, only extensive forms of agriculture, e.g. cultivation of olive and vines, are found on uplands, while highly intensive methods are seen on the alluvial plains. The uplands might have been the granary of the ancient Roman Empire, while the lowlands were uninhabitable at that time, due to poor drainage and malaria. The landscape of the humid tropics in the far future may be such that vast upland areas are covered with Imperata spp. or extremely poor stands of trees with small pockets of cassava fields, while in the alluvial valleys, a very intensive rice-based multicropping system may be practised in an area surrounded by hills covered with tropical trees.

The cultivation of cassava and other root crops has been well adapted to the humid tropics, and so these crops are less vulnerable to climatic variability. However, root crops have other difficulties. For example, they are bulky and perishable unless processed. This may be no drawback in a subsistence economy, but it will become a great disadvantage if these crops are to be staple food for an urbanized society. In the case of the commercial production of cassava for industrial purposes, first, dry tips are prepared and, next, they are processed into tapioca flour. Proper methods for processing, storage, marketing and cooking of cassava and other root crops for direct consumption as food by city dwellers have yet to be discovered. If root crops such as cassava cannot become staple food for urbanized society, farmers will turn to other, more acceptable crops which may not be so suited to humid tropical conditions and thus the vulnerability of this agricultural area to climatic variation will increase.

Trees are also considered to be less vulnerable to climatic variation. However, that does not mean that trees are not at all affected. The following citation may be interesting:

"During one growing season a tree normally stores photosynthates in excess of that year's growth needs. This provides a reserve which is drawn on the following year and makes it possible for the tree to survive a single severe year Those integrative mechanisms mean that the variance spectrum of tree response to climate should show suppressed response to high-frequency climatic variations, but accumulated response to small systematic changes in climate, and such spectra do It is not realistic to say that, because trees survive the large interannual variation, climatic mean changes are unimportant." 11.

The above citation refers to those trees, such as timber and rubber trees, that are not grown for their flowers or fruit. Flower and fruit formation is more sensitive to climatic variation than vegetative growth of trees because stress at a certain phenological stage is critical.

Oil palm plantations in the Malaysian Peninsular are presently expanding at quite a high rate as good replacement for rubber. Malaysia's share in the world's total production of oil palm is 44 per cent. In the case of this crop, the period between the initiation of primordia and the harvest of bunches is from 33 to 36 months, and during this period there are several growth stages which are highly sensitive to rainfall deficiency. A severe drought affected the oil palm area for much of the years 1976-1977. At the end of 1977 the effect of the drought on production was already estimated at a loss of some 50 000 tons. (In 1976, figures for the total

production of palm oil and palm kernel were 1 250 000 and 275 000 tons, respectively.) In view of the long development cycle of the palm bunch, the effect of the 1976-77 drought will certainly still be felt by plantations until mid-1979, although the present steeply ascending trend of oil production in Malaysia will make this loss insignificant 12.

Serious frost damage to the Brazilian coffee crop followed by the price jump in 1975 is still fresh in many memories. It is known that a period of six hours below -2 deg C is sufficient to kill the leaves and that further exposure to cold could cause serious damage in the stem of coffee plants 13. Although frost may cause some damage to coffee on an average of once every three years, the impact of the frost that occurred on 17 July 1975 was very serious (Table 3). But the damage was serious only in two out of the four major coffee-growing states of Brazil, those in the cooler southern area. Figure 13, showing the absolute minimum temperature for July at -2 deg C, explains the severe damage in Parana and Sao Paulo.

Table 3

Coffee production in Brazil

States	1974			1975		
	Area ha	Prod. tons	Yield kg/ha	Area ha	Prod. tons	Yield kg/ha
Minas Gerais	329 300	244 000	759	375 000	330 000	880
Sao Paulo	646 000	864 000	1338	406 000	255 000	630
Espirito Santo	171 520	98 000	571	229 000	155 000	678
Parana	839 000	477 000	568	3 724	264	71

(Data source: Synopse Estatistica do Brasil 1975-77.)

In the major coffee-growing area of Brazil, the mean temperature for the month of July may drop to as low as 16 deg C, and representative average minimum temperatures are of the order of 7-8 deg. C. Though most of the area is north of the Tropic of Capricorn, it may hardly be called the humid tropics climatologically. Frost damage to coffee in Brazil is an example of damage that may affect tropical crops planted in thermally marginal regions.

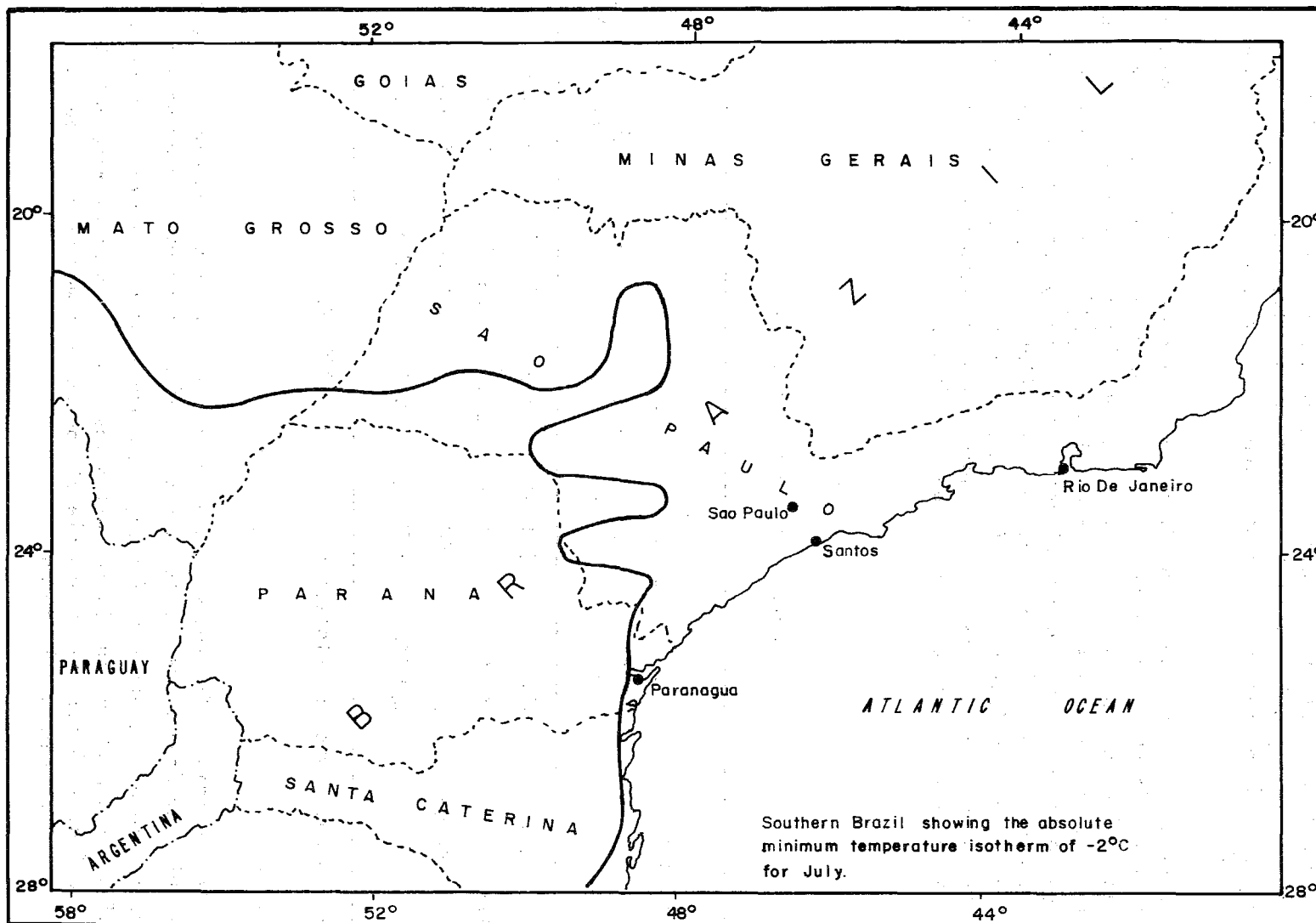


Figure 13. Map showing the absolute minimum temperature for July at -2°C in the coffee region of Brazil.

During the colonial period, a few big political powers commanded vast undeveloped territories in the humid tropics. It was possible to introduce large-scale plantation agriculture anywhere within their territories where environmental conditions were suitable. Thus, the most suitable areas were developed while the less suitable ones were left unused. Under such political and economic conditions, one major role of agro-environmental research was to find the most suitable area for a particular plantation crop. Research in agro-climatology was no exception.

After many of the tropical countries gained their independence and their populations increased explosively, the emphasis in such research shifted from a search for the best agricultural conditions to an attempt to make the best possible use of available resources. In most newly independent countries, development of only the most suitable areas is an unacceptable luxury. This means that many crops, including tree crops, are now being planted in less than favourable environments in terms of soil, topography and climate. Though trees are in general less vulnerable to climatic variability than other short-term crops, particularly the annual grain crops, it is anticipated that the propagation of tree crops to marginal areas will adversely affect their production stability as well.

3. Vulnerability of lowland rice cultivation to climatic variability

Lowland rice cultivation differs in various ways from rain-fed upland crop agriculture as well as from irrigated agriculture in the arid zone. The difference is particularly notable in the mode of the supply of water to plant roots. Therefore, the vulnerability of rice agriculture to rainfall variation is expected to differ substantially from that of other types of cultivation.

In the humid tropics, the population density in the rice-growing region is surprisingly higher than that outside of it [14]. Historically, lowland rice cultivation is the only agricultural system that ever supported great concentrations of population on a sustained basis in the humid tropics. The reason for this is probably the high and stable productivity of lowland rice.

It has been repeatedly mentioned that the eventual degradation of land makes upland crop cultivation highly risky in the humid tropics. Rice cultivation is almost completely free from such land deterioration. First, the depletion of plant nutrients in the soil is compensated by the extra supply of nutrients through peculiarities of paddy cultivation; that is, very active non symbiotic nitrogen fixation, the release of nutrients by strong reduction of soil under submerged conditions, and supply by irrigation water the contribution of which may not be so great as many believe. Such an extensive rice area is not flooded with river water every year or every few years and the nutrients are supplied to an extensive area by anomalous floods which may be disastrous in the year they occur. Second, the levelled paddy plots surrounded with bunds are nearly immune to water erosion. Thus, rice agriculture lacks both fallowing and rotation practices, and yet a certain level of yield can be maintained by planting rice on the same plot year after year.

It is not so simple to compare the productivity of rice with that of other cereals. One to two tons of paddy rice per hectare is the most common level attained without chemical fertilizer in contemporary tropical Asia. This level is no lower than that of wheat in medieval Europe. In terms of the ratio of the number of grains sown to the number harvested, the superiority of rice is more evident. However, the best

terms in which productivity can be compared are the yields per unit land managed by a farmer rather than the yields per unit area harvested. In Europe during the pre-fertilizer period, the portion of one's farm that could be cropped in a particular single year depended on the delicate balance between soil fertility, number of cattle and number of mouths to be fed. How to improve cropping intensity was the central theme of technological progress there. Every plot of one's farm could be cropped year after year, that is, the intensity approached unity only after the development of chemical fertilizer. On the contrary, the cropping intensity is almost always unity in rice-growing Asia no matter how primitive the cultivation techniques. Continuous cropping of lowland rice does not diminish the yield to such an extent that it is no longer worthwhile to cultivate the land.

The stability of rice production can be explained by the following two factors.

- (a) Water ponded by bunding would otherwise be lost as run-off. Therefore, the bunds increase the amount of water available to the plant over that retained by the water-holding capacity of soil. This effect is especially significant when one takes account of the timing and intensity of rainfall in tropical Asia.
- (b) A substantial fraction of rice land is irrigated. It is said that about 20 per cent of rice land in south and southeast Asia is presently irrigated.

Thus, rice agriculture, in general, can be characterized by high and stable productivity. However, this may not always be the case when one looks into the actual situation of rice production. For instance, the difference in productivity between European and Asian agriculture became less pronounced since the land use intensity of the former increased to unity. Yet, in comparison with shifting cultivation, as well as with even the sedentary cultivation of upland crops in the humid tropics, higher productivity of rice agriculture will be maintained for many years to come or will even become more significant.

The supposedly greater stability of rice production compared with other forms of agriculture is not always reflected in actual production statistics (Table 4). Certainly rice production in such countries as the U.S.S.R. and U.S.A., where all rice is irrigated, is much more stable than the production of any other crop. But it is not the case in tropical Asian countries where irrigated rice is only a small portion of all the rice produced.

In Japan, nearly all rice lands are irrigated. Drought affecting lowland rice is now a story of once-upon-a-time. Under such circumstances, therefore, various crop-weather analyses of rice reveal the relationship between rice yield and climatic parameters other than rainfall. An example of such a time-series analysis indicates the significance of solar radiation and temperature during the maturation period of rice as the determinants of rice yield. The negative correlation between yield and rainfall is merely the reflection of the negative correlation between rainfall and sunshine hours (Table 5). A cross-section analysis in which yields of different provinces in Japan were studied also indicates the significance of the same two climatic parameters (Figure 14). A similar result is obtained in experiments under controlled conditions in tropical Asia 17.

Table 4

Year-to-year fluctuation of yields of rice and other crops

<u>Country crop</u>	Coefficient of variation ¹⁾ (CV %)	Total Production ²⁾ (million tons)
<u>U.S.S.R.</u>		
wheat	12.4	85.8
rice	3.6	1.6
<u>U.S.A</u>		
wheat	7.3	42.0
rice	3.7	3.9
<u>Philippines</u>		
rice	6.9	4.9
maize	6.4	2.0
<u>Indonesia</u>		
rice	4.5	18.1
maize	4.1	2.7
<u>Thailand</u>		
rice	5.1	11.8
maize	18.1	1.7
<u>India</u>		
rice	7.1	60.5
wheat	5.4	26.5
barley	8.8	2.5
maize	9.0	5.3
millet	7.7	8.3

1) Based on the de-trended yield during the period of about ten years in the 1960's.

2) In 1970, 1971 or 1972.

(Source: Ministry of Agriculture and Forestry (Japan), 'World Climatic Change and Crop Production', 1974. mimeo. in Japanese.)

Table 5

Correlation of yield of rice in Shimoina district with climatic elements¹⁾

Period	Correlation coefficient with grain yield			
	sunshine hours	mean air-temperature	air-humidity	rainfall
Sept. 3 - Sept. 17 (most active filling period)	0.832	0.323	-0.741	-0.602
Sept. 1 - Sept. 30 (filling period)	0.429	0.184	-0.811	-0.771

1) Based on 15 years data.

(After Oka 1937 15)

It is natural that variations in rainfall do not directly affect variations in yield when water is controlled. This can be seen not only in rice cultivation but also in any other type of irrigated agriculture. What is important to rice agriculture's vulnerability to rainfall variability is the extent and the rate at which irrigation facilities are implemented.

Irrigation of rice in the traditional Asian rice zone and that in the arid zone may be basically quite different. Some peculiar features of the irrigation for rice are listed below.

Figure 15 shows the percentage of irrigated and rice acreage of 76 countries with more than one million hectares of arable land. Group I in the figure consists of 46 countries where less than ten per cent of the arable land is irrigated and less than ten per cent is planted in rice. These countries are found in non-Mediterranean Europe, the Americas and Africa south of the Sahara, where rain-fed upland crop agriculture is dominant. Group II comprises 14 non-rice-growing countries in which irrigated lands exceed ten per cent of the total arable land area. These countries are in the Mediterranean region, North Africa, the Middle East and parts of South America, where irrigated agriculture is practiced in a substantial portion of the countries' arable land.

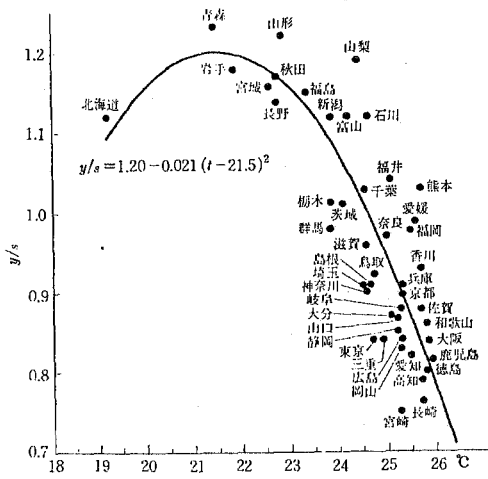


Figure 14. Relation between temperature¹⁾ and ratio y/s ²⁾³⁾

- 1) Mean temperature in August and September
- 2) y : yield of brown rice in kg per hectare (average of 1957-1961)
- s : mean of solar radiation in $cal/cm^2/day$ in the same two months
- 3) Each dot denotes the 46 provinces in Japan

Source: 16.

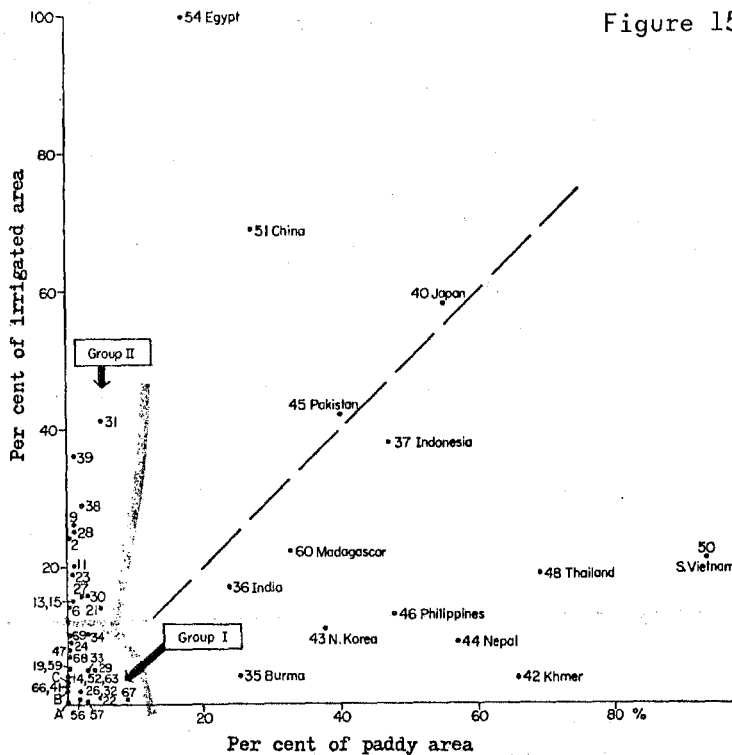


Figure 15. Percentages of irrigated and rice areas to total arable area in 76 countries (Source: FAO production year-book, vol. 25. (1971))

2 Bulgaria, 6 France, 9 Greece, 11 Italy, 13 Portugal, 14 Rumania, 15 Spain, 19 U.S.S.R., 21 Cuba, 22 Guatemala, 23 Mexico, 24 U.S.A., 26 Bolivia, 27 Brazil, 28 Chile, 29 Colombia, 30 Ecuador, 31 Peru, 32 Uruguay, 33 Venezuela, 34 Afganistan, 38 Iran, 39 Iraq, 41 Jordan, 47 Syria, 52 Algeria, 56 Ghana, 57 Ivory Coast, 59 Libya, 63 Morocco, 66 Rhodesia, 67 Sierra Leone, 68 S. Africa, 69 Sudan, (A) Austria, Denmark, Finland, Poland, Sweden, Canada, Burundi, Ethiopia, Kenya, Melawi, Mali, Niger, Nigeria, Togo, Tanzania, Uganda, Upper Volta, Zambia. (B) Hungary, Yugoslavia, U.K., Tunisia. (C) Czecko-slovakia, E. Germany, W. Germany, Argentina, Turkey, Australia.

Countries with more than ten per cent rice area are shown in the wide space at the right hand side of the figure. Four countries among them, i.e. Egypt, China, India and Pakistan, differ from the other rice-growing countries in that irrigated agriculture as seen in the arid zone of the Group II countries is dominant in large areas. Therefore, the relatively high percentage of irrigated area in these four countries does not necessarily indicate a high percentage of irrigated rice area. In the rice-growing countries other than these four, most of the irrigated area is devoted to rice. In the ten countries forming this group, the percentage of irrigated rice land ranges from eight in Khmer to 56 per cent in Japan. This wide variance is not related to rainfall which is the decisive element determining the percentage of irrigated area in the Group I and II countries. In the rice-growing countries plotted close to the diagonal line in Figure 15, such as Japan, Madagascar and Indonesia, it is not the case that irrigation for rice is required due to scarce rainfall and it is not the case either that in those countries with a low percentage of irrigated area, irrigation is not required thanks to favourable rainfall.

Assuming that there is no irrigation, the water balance of rice fields can be estimated by some conventional method such as Thornthwaite's. An example of such a calculation applied to tropical Asia is introduced here 18. Since rice fields are surrounded by bunds to pond water, Thornthwaite's method was slightly modified: a maximum of 200 mm of water can be retained by bunds as the surface water layer in addition to 100 mm in soil solum. Among 125 stations' data from South and Southeast Asia, the period during which rice fields can be inundated was found to be less than two months at 50, three months at 14, four to six months at 39 and more than seven months at 22 localities. Figure 16 shows the water balance at some representative locations. The study concluded that "the greater part of the rice lands in Pakistan, India, Thailand and Cambodia are either prohibitive or marginal for rice cultivation unless the land is artificially irrigated or naturally inundated due to physiographic conditions". It is these countries (except for Pakistan) rather than those in more humid insular Southeast Asia that form the core region of the Asian rice zone, and yet the irrigation ratio is not particularly higher in the former than the latter.

Two characteristic features of the rice-water relationship were mentioned above, that is,

- (a) the irrigation ratio is not related to the amount of rainfall in rice-growing Asia, and
- (b) assuming no irrigation, the water balance is very unfavourable or even prohibitive for rice cultivation in the very core region of the traditional Asian rice zone.

To understand these seemingly contradictory features and other peculiarities of rice cultivation, a comparison with other types of agriculture will be useful. In terms of water use, three types of agriculture can be distinguished. The first type is rain-fed upland crop agriculture, the most dominant form of agriculture on the earth. In this type, water supplied to crops is derived solely from rain water falling precisely on each patch of the fields, in other words, direct rainfall. Water supply by irrigation or use of groundwater is unusual. Therefore, apart from rainfall itself, the dominant factors governing the supply of water to plant roots are evaporation, water-holding capacity and permeability of the soil.

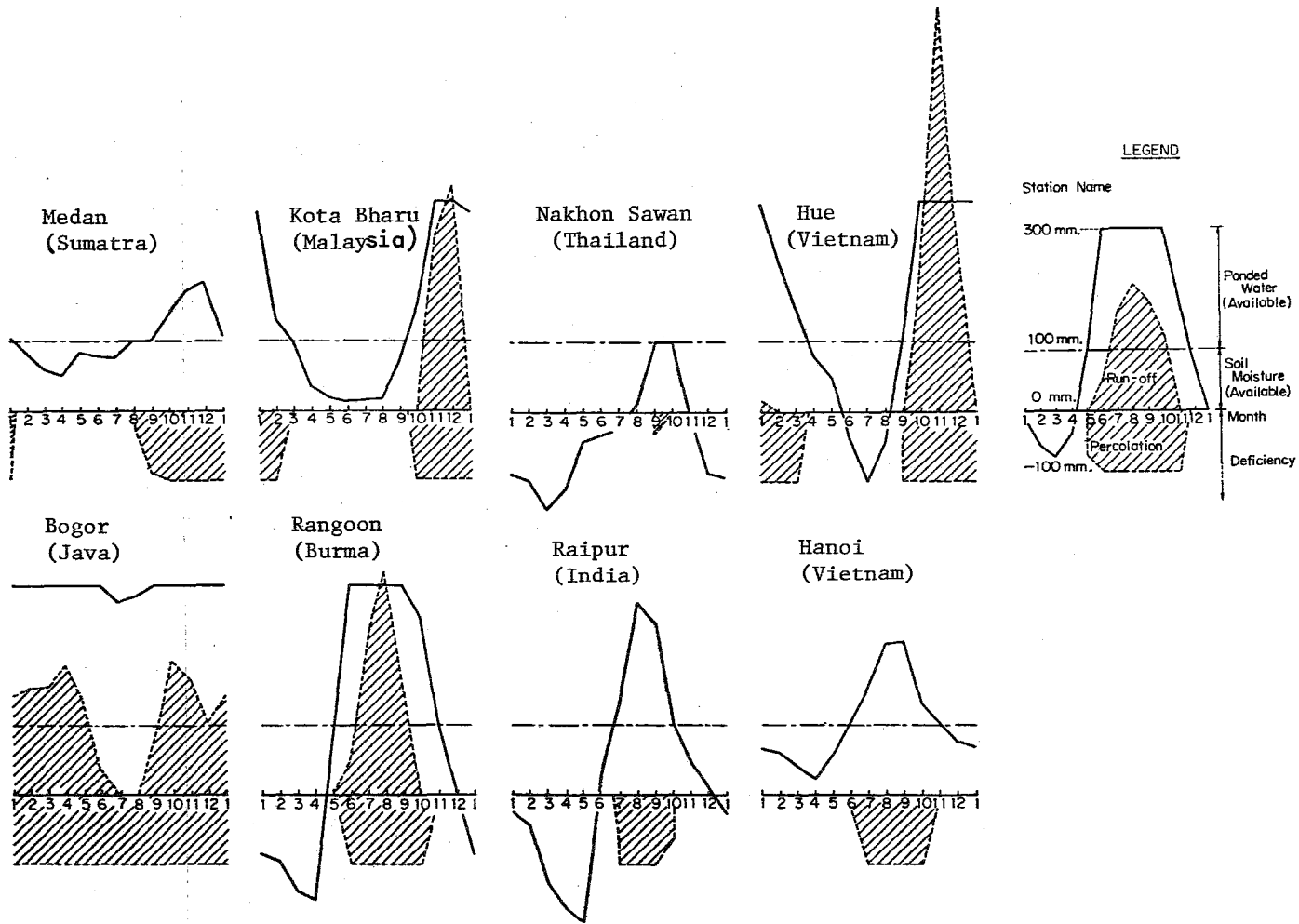


Figure 16. Pattern of soil water regime at selected stations in South and Southeast Asia (From Kyuma 1973 18)

The second type is irrigated agriculture in the arid zone, in which direct rainfall has no significance. Most, if not all, of the water supplied to crops is carried from distant places where precipitation is abundant. Therefore, the dominant factors determining water supply are primarily of an engineering nature and involve some agronomic qualities of soil.

The third type is rice agriculture, in which the crop depends on both direct rainfall and the rain water which falls on the catchment area and eventually flows to where the crop grows. The catchment area could be a village compound a few metres away or mountains hundreds of kilometres away. The flow of water from the catchment could be natural or artificial. Careful observation reveals that there seldom exists so-called 'rain-fed' paddy land in the strict sense of the term.

In the non rice-growing countries, crops depend nearly exclusively either on direct rainfall or on irrigation water. Where the former is dependable, the latter is unnecessary. Where it is not, irrigation becomes indispensable. Therefore, it is a natural consequence that percentages of the irrigated area are closely related to climate in the non rice-growing countries. In these countries, agriculture practised in the irrigated tracts is completely different from that of the unirrigated land, that is, if there exists any agriculture there. The demarcation between the irrigated land and the unirrigated land is very distinct, no matter what irrigation devices are used.

In the rice-growing countries, on the contrary, the crop always depends partly on direct rain and partly on the inflow of water. The degree to which artifacts control the latter source of water varies widely. Some paddy fields appear to be nearly entirely rain-fed while some others may be equipped with a complete water control system. The dependability of direct rainfall certainly is one of the determinants affecting the degree to which artifacts are used to supply water inflow; this degree varies between the two extremes mentioned above. However, many other factors than rainfall affect the use of water control devices. One of the most important factors is the level of technology required, which is primarily determined by the inherent physical conditions of the land. Apart from these natural factors, various socio-economic and cultural factors are closely related to the degree of water control. The historical interrelationship between development of irrigation systems and political structure is a well-known example. The fact that there is no relationship between rainfall and the irrigation ratio in the rice-growing Asia can be explained in this way.

As long as the sources of water for rice lands are not only direct rainfall but also rain water falling on catchment areas, it is quite understandable that the ratio of the catchment to the rice area is of prime importance. This ratio together with rainfall itself roughly determines potential rice acreage and stability of production.

As Koide has pointed out, the rice-growing areas are found mainly in the Alpine orogenic belt /19/. Most of the high mountains in the world today are in this geologic zone, which is characterized by an abundance of steep slopes. Where this zone overlaps that of a warm and humid climate, rapid weathering and transportation and sedimentation of weathered materials result in the development of alluvial plains. As shown in Table 6, a large area of alluvial plains is found in the Asian humid zone, and they make up a high percentage of the total land area. The Asian rice zone is situated in that part of the Alpine orogenic belt that has a warm and humid climate.

Table 6

Importance of alluvial land in Asia (in million hectares)

	Land Area		Alluvial Soil Area	
	Total	Potentially arable	Total	Potentially arable
World	13 000	3 152	588	316
Asia ¹⁾	2 704	620	-	192
Tropical Asia	987	344	168	114

1) Excluding USSR (Source: World Food Problem, White House, 1967)

As a natural consequence of the alluvia-forming processes, the alluvial plains are always surrounded by steep mountains. The landform of the Asian rice zone is characterized by a pattern consisting of a large area of steep mountains and a small area of alluvial valleys. Rice agriculture in Asia as a whole owes its existence mainly to the ratio of the catchment area (mountains) to rice land (alluvial plains). Contrary to this, the landform of the rain-fed agricultural zone is characterized by vast plains with gentle slopes developed on tectonically stable land masses.

This difference in basic landforms of the rice agriculture and rain-fed agriculture zones can be well demonstrated by comparing the percentages of agricultural land to total land area among the countries belonging to the three groups illustrated in Figure 15. In the rice-growing countries, these percentages are always low in spite of a generally warm and humid climate and very great population pressure. These low percentages in the rice-growing countries are attributable to a large area of steep mountains which serve as the catchment area.

Two studies of rice production in Thailand also illustrate the significance of landform as a determinant of the hydrological condition of paddy lands.

In one, the interregional variation of rice production in Thailand was studied ^[20]. Traditional methods of cultivation, productivity, holding area per farm family, kind of water control devices, etc., vary substantially from one place to another within the Chao Phraya river basin. First, these variations in aspects of production were examined. Second, all the paddy land within the basin was divided according to different environmental conditions such as topographical, hydrological, and soil conditions into six physiographic regions. As the hydrological, and soil conditions are strongly governed by the topography, the resulting physiographic regional division was found to be mainly determined by landform rather than rainfall and soil. Third, such a physiographic regional division was correlated to the interregional variations of rice production, and it was found that these variations could be very well explained by the physiographic conditions (Table 7). This study discussed the potential dissemination of high-yielding varieties of rice based on such regional divisions.

Another study ^[21] on rice production in Thailand is more directly related to the vulnerability of rice cultivation to rainfall variation. First, the coeffi-

cient of variation of rice production was calculated for each of the 28 provinces which are major rice-producing provinces in Thailand, and whose rainfall and production data have been sufficiently reliable and consistent for at least 15 years. The waterbalance for the period of four rice-growing months was calculated by Thornthwaite's method assuming the extra 200 mm of ponded water. The topographical characteristics of each province are more difficult to quantify than the other elements. In this study, an attempt was made to quantify them in terms of the ratio of recent alluvial soil area to the total paddy land area.

Table 7

Regional division of the Chao Phraya Basin (Source: Fukui, H. $\sqrt{21}$)

RICE-CULTURAL REGION	PHYSIOGRAPHY	WATER CONDITIONS		SOIL FERTILITY	MODE OF CULTIVATION	PADDY YIELD (ton/ha)	RICE AREA CULTIVATED PER FARM FAMILY (ha)	PADDY PRODUCTION PER FARM FAMILY (ton)	APPROXIMATE RICE AREA (\times 1,000 ha)
Traditional irrigation area	Intermontane basins	Gravity Irrigation	Governmental Communal	Medium	Transplanted	2.5-3.0	1-2	2-4	320
Water-deficient foothills	Fan-terrace complex area		Communal, both effective and ineffective						
Inland flood area	Constricted river channel area	Conservation Irrigation	Uncontrolled	Medium	Broadcast	1.5-2.0	4-5	6-8	200
Barrage irrigation area	Old delta	G.I.	Governmental	Medium	Transplanted	1.8-2.2	3-4	5-7	80
			Uncontrolled	High	Broadcast	1.8-2.2	3-5	6-8	310
Canalled lowland	Delta flat	Conservation Irrigation	Uncontrolled	Low	Broadcast	1.0-1.5	5-7	6-10	750
Less-flooded delta	Deltaic high		Controlled						

Figure 17 shows the year-to-year fluctuations of rice production and the seasonal rainfall in some representative provinces. When both the rainfall and the ratio of alluvial soil area are high, production is stable (Figure 17a), while it is highly unstable when both are low (Figure 17b). In Chiang Mai, production is relatively stable although the amount of the four months' rainfall is less than 1 000mm in most years (Figure 17c). This can be attributed partly to the high ratio of alluvial soil area in this province. Where the rainfall and the ratio are neither particularly high nor low, the production variability is somewhat between the two extremes (Figure 17d and 17e).

The simple correlation coefficients (r) were found to be rather small between CV of production and either the seasonal water balance or the ratio of alluvial soil area alone. But the multiple correlation was more significant when both were correlated with production variability (Table 8).

Opening of new land to rain-fed upland crop agriculture is nothing but the replacement of the original vegetation by crops. The moisture regime remains basically unchanged before and after reclamation. Once land is reclaimed, man's efforts are directed toward preserving the original land condition as well as possible.

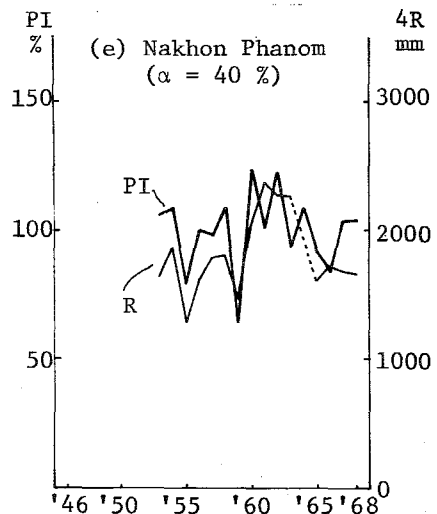
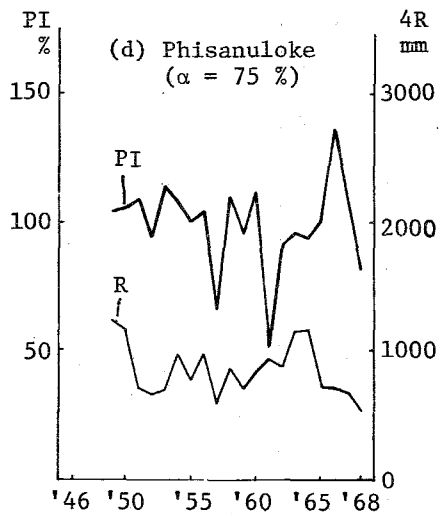
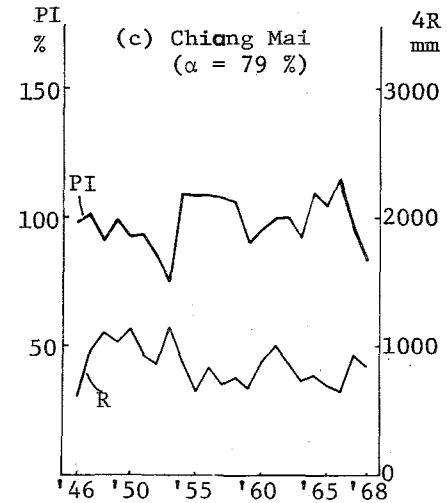
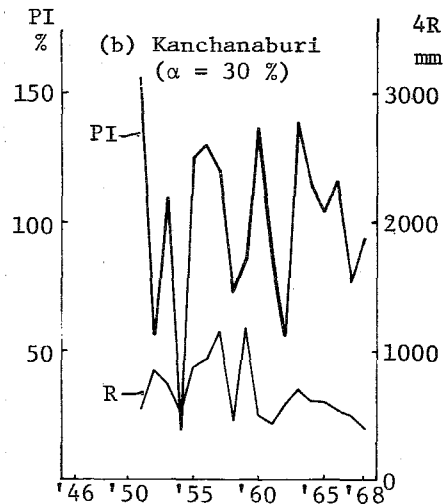
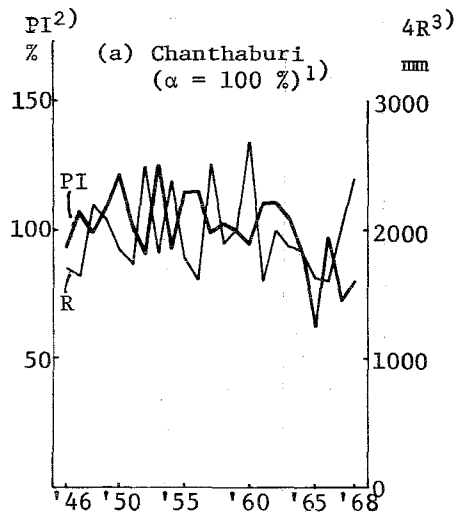


Figure 1Z. Year-to-year fluctuation of rice production and seasonal rainfall at selected provinces in Thailand.

- 1) Percentage of recent alluvial soil area to total rice land area
- 2) Production index (de-trended)
- 3) Sum of 4 months rainfall total

Table 8

Correlation of cross-province variation of rice production's year-to-year fluctuation with climatic and topographic parameters

		Simple correlation coefficient (r) between CV of production in each of 28 provinces, CV(PRO) ² , and
Mean rainfall total in four rice-growing months	$4\bar{R}$	-0.284
CV of the above	CV(4R)	0.297
Mean of sum of monthly water balance in the same four months ³⁾	$4\bar{W}$	-0.434
Median of the above	4W(M)	-0.429
Percentage of recent alluvial soil area to total paddy land area	α	-0.465
Rate of increase of paddy area	H	0.425
		Multiple correlation coefficient (R) between CV(PRO) and
4W(M) and α		0.583
4W(M), α and H		0.645

- 1) The period for which calculation was made varies from one province to another depending on availability of consistent data. It ranges from 15 to 30 years.
- 2) CV(PRO) is based on the de-trended production data.
- 3) Water balance was calculated according to Thornthwaite's method assuming the extra 200 mm of ponded water.

(After; Fukui, Uchida and Kobayashi. Unpublished.)

All he can do to improve the land is to modify the original nutrient-supplying capacity of the soil, that is by manuring. In order to maintain good land conditions, various methods such as fallowing, crop rotation, the combination of crops and animals, contour

cultivation and so on are employed. All of these practices characteristic to upland crop agriculture are absent in rice agriculture.

As long as land conservation rather than land improvement is man's main work in a given environment, the discovery and improvement of crop species and varieties become very important as a means of mitigating the restrictions imposed by physical conditions. Therefore, the general direction of technological progress in rain-fed upland crop agriculture is toward better conservation of land and adaptation to a given environment rather than amelioration of it. As a result, in this type of agriculture, no single crop occupies such a predominant position as rice in rice agriculture. On the contrary, different crops are chosen according to local agro-environmental conditions in the same way that the type of natural vegetation is determined by these conditions.

When a tract of land is opened for rice cultivation, the land is levelled and surrounded with bunds to impound water from direct rain as well as local run-off, streams and/or rivers. In the case of rice agriculture, reclamation is not merely, the replacement of original vegetation for rice, but it is also the creation of a new environment which does not exist in nature. The resulting hydrological condition of such a man-made environment is a function of both a given physical setting and the extent and nature of the structures used to modify it.

Since such measures for improving the hydrological condition of paddy fields always progress steadily, the terms 'irrigated' and 'unirrigated' are not always adequate for designating the actual hydrological condition of the land tract. It can be said that man's efforts in rice agriculture are directed mainly toward amelioration of the conditions of the land and water, rather than toward land conservation. In other words, the cumulative toil of past generations has created the land and water conditions of the paddy fields.

In the traditional rice-growing countries, land used for rice and land used for other field crops are commonly called by different terms, and all of the arable land is considered to consist of these two kinds of land which usually cannot be converted into each other. For example, these fields are called 'ta' and 'hata' in Japanese, 'na' and 'rai' in Thai, and 'sawah' and 'ladang' in Malay and Indonesian. These expressions reflect not only differences between the two in their inherent physical conditions but also the great amount of labour expended for generations on the rice land.

The above discussion indicates that the control of water for rice cultivation is basically of a different nature from so-called 'irrigation' in other types of agriculture. In the former, at the very beginning of land reclamation, water is already controlled by some measure, and the hydrological condition is gradually improved thereafter, until water is so completely controlled that rice production is no longer affected by rainfall variability. In the latter case, irrigation is an all-or-nothing matter. It drastically changes the whole system of agriculture. In rice agriculture, water control is a built-in characteristic of the system, though the degree to which it is used varies widely. Water control can be likened to a road system which begins with foot paths and is improved to make cart roads, then single lane roads, double lane roads and finally, highways. Thus, such a system can be called an infrastructure rather than one of the inputs needed for production.

Everywhere in the traditional rice zone in Asia, farmers are doing their best to improve hydrological conditions; moreover, water is nearly completely controlled in some advanced countries in the Far East as well as some localities in tropical Asia. These facts suggest that the hydrological conditions of all the paddy lands in Asia should and will eventually be perfected and that production will become free from the erratic rainfall regime.

Figure 18 and Figure 19 reflect this idea. In the first figure, the estimated yield increase of rice in Japan since the sixth century is shown, and on this curve, the present yield levels of Asian countries are plotted. In the second figure, the national paddy yield of these countries is related to the percentage of irrigated area. These two figures appear to suggest that rice agriculture evolves from the low yield level with poor water control to the high yield level with better water control, and the countries with lower yield and poorer water control can be located at certain stages of this evolutionary sequence which the better-off countries have passed some time earlier.

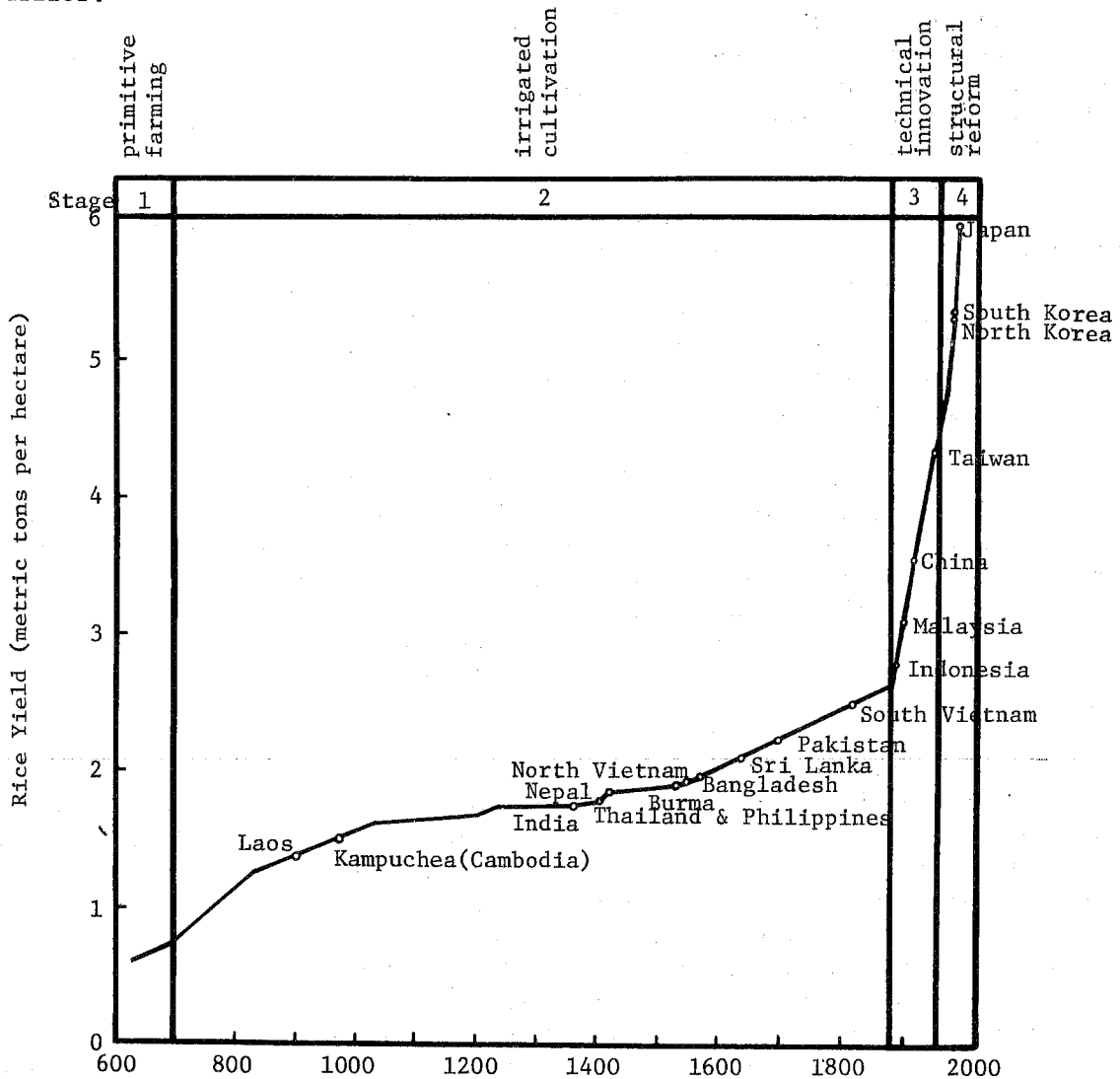


Figure 18. Correlation of intensification of farming and yield of rice (based on historical progress of rice production in Japan). (From: Report of the Trilateral Food Task Force [22])

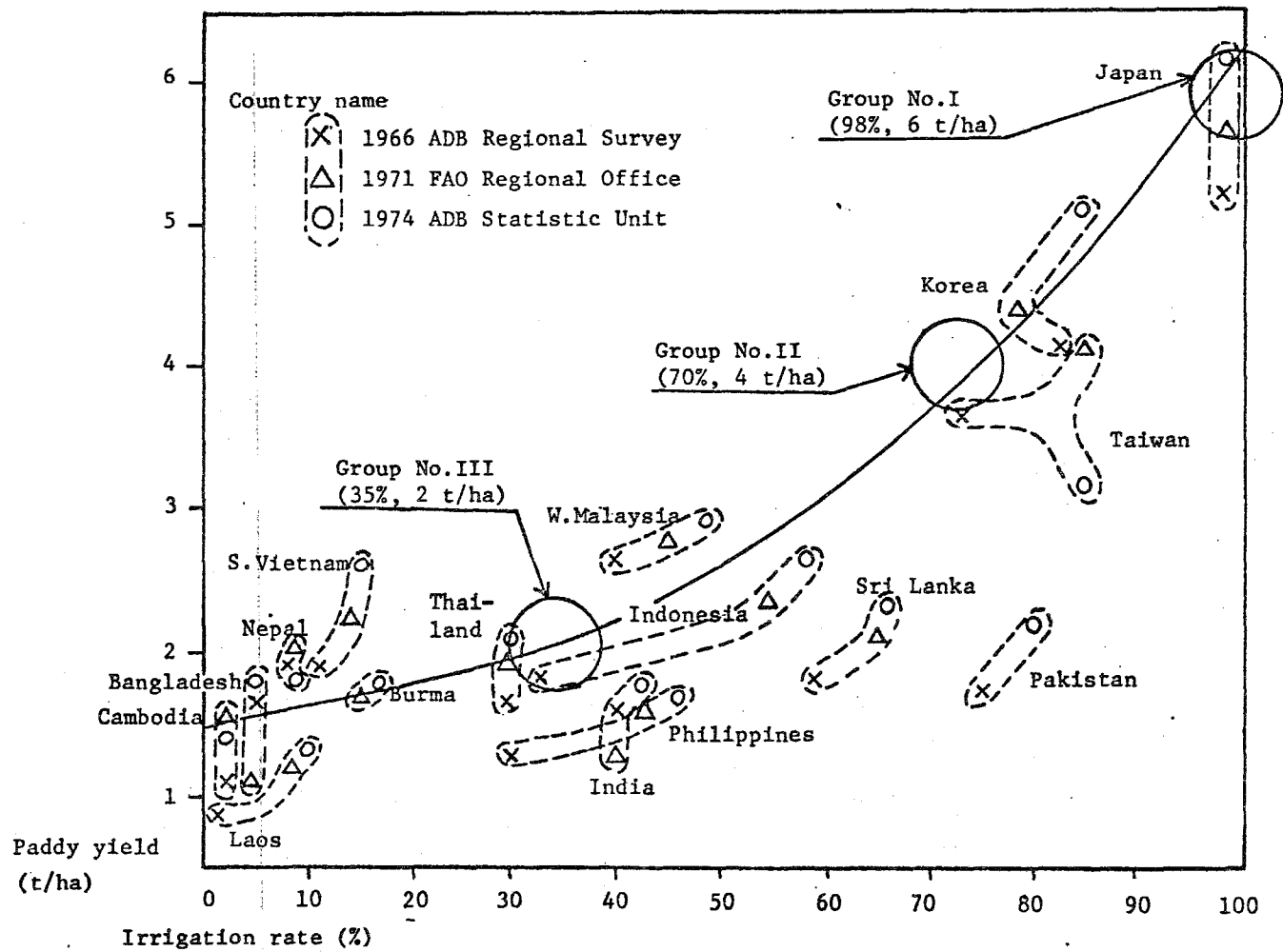


Figure 19. Relation between irrigation rate and paddy yield. (From: Okita and Takase, 1976 23)

The fact that the actual water condition of rice lands is so diverse and complex that it is not adequate to classify these lands simply as 'irrigated' and 'rainfed' is becoming widely recognized. For instance, there is an attempt to classify the world's rice land according to the depth to which fields are inundated (Table 9). The much heralded high-yielding varieties of rice bypassed the rice grown in areas with less favourable physical (mainly hydrological) conditions. Such a classification is relevant to the development of a technology of production adapted to variable hydrological conditions.

Table 9

General association of hydrology class to landscape position

Hydrology	Water table	Landscape position
Pluvic	Deep water table	Knolls and summits of rolling and hilly topography
Perfluxic	Deep ground water table, highly fluctuating perched water table	Upper side slopes of knolls and summits of rolling and undulating topography
Orthofluxic	Deep water table less fluctuating perched water table	Lower side slopes and water ways associated with rolling and hilly topography
Orthocumulic	Ground or perched water table fluctuate close to soil surface during wet and intermediate months	Lowest paddies on the side slopes, high plains, and low plains
Percumulic	Ground or perched water table is almost consistently above ground level (GL) during wet months	High plains with high phreatic and surface enrichment and water ways associated with high plains; low plains
Orthodelugic	Water table rises more than 30 but less than 50 cm above GL and stays for more than two weeks during wet and at most one intervening intermediate rainfall month	Water ways and back swamps associated with cumulic low plains subject to inundation
Perdelugic	Water table rises above 50 cm but less than 100 during wet and at most 2 intervening intermediate rainfall months	Landscape position similar to Orthodelugic

(From; Zandstra, H.G., et al. IIRI. mimeo.)

To divide rice lands into 'rain-fed', 'inadequately irrigated' and 'adequately irrigated' lands is the first step in the programme for doubling rice production in Asia in 1990. ^[23] The criterion for judging the adequacy in this classification is whether the length of the irrigation canal is longer or shorter than 50 metres per hectare of rice land.

In Table 10, the present, projected, and potential irrigation areas of the tropical Asian countries are compared with the 'adequately irrigated rice area' and 'rainfed rice area' which are targeted for doubling rice production by 1990 ^[23]. The potentially irrigable area was estimated based on existing data, and where such data are unavailable, by simply multiplying the present irrigated area by 2.5 or the projected area by 2.0 or 1.5 ^[24]. Therefore, the potential area is grossly underestimated for most underdeveloped countries, such as Laos and Cambodia. Except in India, most of the potentially irrigable land will be used for rice cultivation. Taking these points into consideration, the table indicates that the eventual completion of water control for most, if not all, of rice lands in Asia is not too unrealistic.

In rain-fed upland crop agriculture, it is unavoidable that production will be substantially affected by the year-to-year variation of rainfall. Even where production technology is most advanced, such as in the developed countries in the temperate zone, the coefficient of variation of grain production in a large area such as the whole U.S. or U.S.S.R., ranges from eight to twenty per cent. This figure becomes still larger when the production of smaller regions is considered. Progress in technology, mainly in genetic improvement, soil conservation, and, perhaps, weather forecasting, might further stabilize production, but to a limited extent.

On the other hand, rice production could be stabilized to a much greater extent by improvement of the hydrological condition. However, whether or not this potential stability can actually be realized depends on:

- (a) the rate of implementation of water control facilities, and
- (b) the rate of expansion of the rice area to increasingly marginal lands.

The rate of expansion of rice land as well as that of lands under other agricultural systems will depend very much on the increase of productivity per unit area on the land now in use.

According to Grigg ^[25], "Between 1870 and 1930 most of the new arable land (in the world) came in the mid-latitude temperate grasslands However, in the 1930s the expansion of this frontier came to a halt," first because "the attraction for migrants was no longer the land but the cities" and, secondly because of "a major agricultural revolution in western countries Since then (the 1940s) the increase in population ... has led to a remarkable increase in the arable area" in China, India, Africa and Latin America. This was because "the need for extra food was naturally met by reclaiming new land To what extent the rapid expansion of the arable area ... will continue, it is difficult to say. Continued population increase and the expansion of a landless rural proletariat favour further increases in arable land. On the other hand, the first sign of intensification in Asian agriculture - the Green Revolution - and the steady drift to the towns suggest that the new frontier of the underdeveloped world may well close before the end of the century, and before the supply of cultivable land runs out."

Table 10

Present, projected and potential area of irrigation in Asian rice-growing countries

Country	Paddy area harvested in 1974 ¹⁾	Irrigated rice area in 1974 ¹⁾	Potentially irrigable area ²⁾	Rice acreage needed for doubling production in 1990 ¹⁾	
				'adequately irrigated'	'rainfed'
(in thousand hectares)					
Bangla Desh	9 904	495	6 800	6 461	3 370
Burma	4 974	797	2 753	3 109	1 690
Cambodia	555	17	470	1 504	780
India	37 500	16 100	80 940	20 890	12 720
Indonesia	8,537	4 950	5 265	4 433	2 900
Laos	686	69	66	583	310
W. Malaysia	597	287	732	(382) ³⁾	(203) ³⁾
Philippines	3 539	1 590	3 189	1 953	1 200
Sri Lanka	680	449	1 000	341	231
Thailand	7 734	2 860	4 000	4 418	2 625
Total of 10 countries	74 706	27 614	105 215	44 074	26 029
Total excld. India	37 206	11 514	24 275	23 184	13 309

1) Okita and Takase 1976 23. 2) Moen and Beek 1974 24. 3) Total of East and West Malaysia

As long as the area of agricultural land is expanding at a great rate, the vulnerability of agriculture to rainfall variation will remain great or tend to increase no matter what crops are cultivated. Only when people begin to divert their efforts toward intensification of cultivation will production be stabilized. But the sustained production of upland crops appears to be much more difficult in the humid tropics than in the temperate zone. Perhaps intensive rice cropping will be the only alternative in larger parts of the humid tropics, including those countries where rice cultivation is not common at present.

4. Conclusions

- (a) In order to assess the impact of climatic changes on agriculture, data concerning not only the changes in means of climatic parameters but also the changes in their distribution pattern are required.
- (b) The impact of climatic changes on agriculture depends on both the amplitude of such changes and agriculture's vulnerability to climatic variability. This vulnerability varies according to the region where cultivation is practised, and also changes over time; such variations might sometimes be more relevant than climatic changes themselves. Agricultural scientists should play a major role in assessing the impact of climatic changes on agriculture by analyzing the space and time variations of the vulnerability of different agricultural systems to climatic variations.
- (c) Agricultural production in the humid tropics is affected by the year-to-year variations of rainfall, though the ~~zone~~ receives a great amount of rainfall. The reason for this is not necessarily the great variability of annual rainfall there. Rather, it is primarily hydrological marginality due to the great amount of evapotranspiration in the economically most active parts of the humid tropics.
- (d) Cultivation of annual grain crops is highly risky in the humid tropics because of the probability of eventual land deterioration and susceptibility to rainfall variability. Cultivation of these crops under the shifting cultivation system does not necessarily cause land deterioration as long as the land-people ratio is above a certain level. However, a sparsely scattered population in remote areas is detrimental to the nation's development and modernization. Therefore, the shifting cultivators tend to concentrate in certain areas either spontaneously or under some resettlement scheme and this makes their agricultural production riskier. Sedentary cultivation of upland field crops by peasants is always expanding to marginal regions because of the scarcity of land suitable for cultivation of crops that are better adapted to the humid tropical environment. The recent development of feed crop cultivation for the export market is similarly risky. The technology needed to grow these crops on a sustained basis may be known, but it does not seem that the majority of peasants will utilize it in the near future.

Nonetheless, it is necessary to continue to grow these crops in regions under any of the three systems of cultivation mentioned above. Therefore, the vulnerability of agriculture in these regions to rainfall will remain great or even increase for many years to come.

- (e) Root crops are well adapted to the humid tropics and so their cultivation is less vulnerable to rainfall variations than are many other crops. However, root crops are not suitable as staple food for urbanized society unless they are processed properly. The technology for processing these crops for urbanized society will affect the future trend of root crop agriculture.
- (f) Tropical tree crops are, in general, less vulnerable to rainfall variability than are short-term crops. But in recent years, they have tended to be grown in increasingly marginal lands. Therefore, one should not be too optimistic about the vulnerability of the cultivation of these crops to rainfall variations.
- (g) Lowland rice cultivation is the agricultural system best adapted to humid tropical conditions. Its vulnerability to rainfall variations could be decreased further by better water control. Water control for rice is basically different from the conventional concept of irrigation in the arid zone. In rice agriculture, not only the vertical movement of water, that is, direct rainfall, evapotranspiration and percolation, but also its horizontal movement, play an important role. The latter is controlled by man to a certain degree of efficiency. The degree to which artefacts control the horizontal movements of water varies widely according to physical conditions and human elements. Since human elements are significant determinants of the hydrological condition of rice land, such a condition is highly time-dependent. Rice agriculture evolves step by step from a low level of production with poor water control to a higher level with better water control. It is not too unrealistic to expect that all rice lands in Asia will eventually be equipped with adequate water control facilities and that rice production will be unaffected by rainfall variability. However, rice cultivation is also expanding to increasingly marginal areas. The vulnerability of rice agriculture as a whole to rainfall variations will be affected by the rate of expansion of the area cultivated on the one hand and, on the other hand, the rate of improvement of water control.
- (h) In the whole humid tropical zone, population has been increasing at a high rate since the 1930s. The ever increasing need for food could be met by either the expansion of cultivated land area or an increase in yield per unit area by intensifying cultivation. So far, the former occurs more often than the latter. As long as this trend continues, the vulnerability of agriculture to rainfall variability will increase in the humid tropics. Therefore, the impact on future agriculture of a greater frequency of anomalously dry years due to climatic changes would be greater than that in the past and present in the humid tropics.

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CLIMATIC VARIABILITY AND AGRICULTURE

IN THE SEMI-ARID TROPICS

Francesco Mattei*

1. Introduction

The arid and semi-arid regions extend widely over the land surface of the world: it has been calculated that at least 40 per cent of the continental surface shows a more or less consistent deficit between precipitation and possible evaporation and 20 per cent may be considered as semi-arid land where cropping systems are practicable even though some rainfall deficit usually occurs.

It is obvious that agricultural systems in semi-arid areas are more subject to the vagaries of the weather than elsewhere and this dependence tends to be greater with the increasing aridity of the area concerned. Moreover, the environment in the semi-arid zones is generally more fragile than in humid zones since, during the long dry season, soil and vegetation are subject to adverse factors such as dry and strong winds, a large day-night range of temperature and a high rate of potential evapotranspiration (PET). The natural mechanisms of recovery of natural fertility are therefore weaker and more affected by adverse external conditions. Consequently, agriculture represents a difficult activity for farmers, who constantly attempt to overcome the climatic constraints through the use of specific forms of soil management (deep ploughing, terracing, fencing, etc.) in order to store the scarce rainwater.

On the other hand, particular cultivation techniques, such as timely sowing and selection of suitable species or varieties with a growing cycle and physiological characteristics that fit the optimum climatic conditions, have been utilized by farmers for a long time in the dry zones where water for irrigation is not available. Nevertheless, the high variability of the climate does not allow satisfactory yields to be obtained easily by the farmers.

Semi-arid lands are present in many parts of the world. It is obvious that, although the general problems and constraints for agriculture are basically the same, the techniques of land management and use may be very different according as to whether cold, temperate or tropical semi-arid lands are concerned.

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In the tropics the occurrence of high temperatures during the rainy season, which usually takes place in summer, gives rise to a series of problems which do not exist in the temperate semi-arid climates with a rainy season in winter. In the latter areas, low temperatures mean a reduced evapotranspiration rate, low plant growth during the rainy season (with easy water storage in the soil) and limited activity of pests and diseases. The final phases of growth occur at the end of the rainy season, with a high level of radiation and good soil water reserves.

In most tropical areas, rains start just after the time of peak temperatures; the first showers are generally lost by fast evaporation from bare soil before any sowing becomes possible; moreover, during the rainy season evapotranspiration is rather high, so the occurrence of dry spells often presents a risk of stress for plants. Finally, the persistence of both high humidity and high temperature throughout the possible growing season means a greater risk of pests and diseases.

From the above considerations, it follows that:

- (a) The limit for rain-fed agriculture in the tropics lies at approximately the 400 mm isohyet, whereas it is at the 250 mm isohyet in temperate zones. With the same rainfall, therefore, the possible growing season is much shorter in the tropics (Figure 1).
- (b) With an equal amount of rain, the yields of traditional agriculture are lower in the tropics (400-700 kg/ha of grains against 800-1 000 kg/ha in the temperate zones with 400-600 mm of rainfall).
- (c) The influence of weather variability on agriculture is much greater in the tropics.

In conclusion, the analysis of the relation between climate and agriculture should follow separate approaches in the tropics and in temperate zones. The results cannot be easily interchanged from one environment to another.

2. Background

2.1 Agroclimatic classification of semi-arid tropics

The existing climatic classifications (due to Thornthwaite, Koeppen and others) are inadequate to explain the relationship between climate and land use. This is due to the fact that the climatic data usually considered in such classifications (mean temperature, total yearly rainfall) are unable to explain the numerous agricultural systems and techniques used by farmers in terms of weather and climate.

In particular, in tropical environments the fairly high temperature during the rainy season does not represent a limiting factor for the growth of tropical crops, whereas the amount and distribution of rainfall, as well as the evapotranspiration rate, are of paramount importance in determining the length of possible growing seasons and, consequently, the cropping patterns.

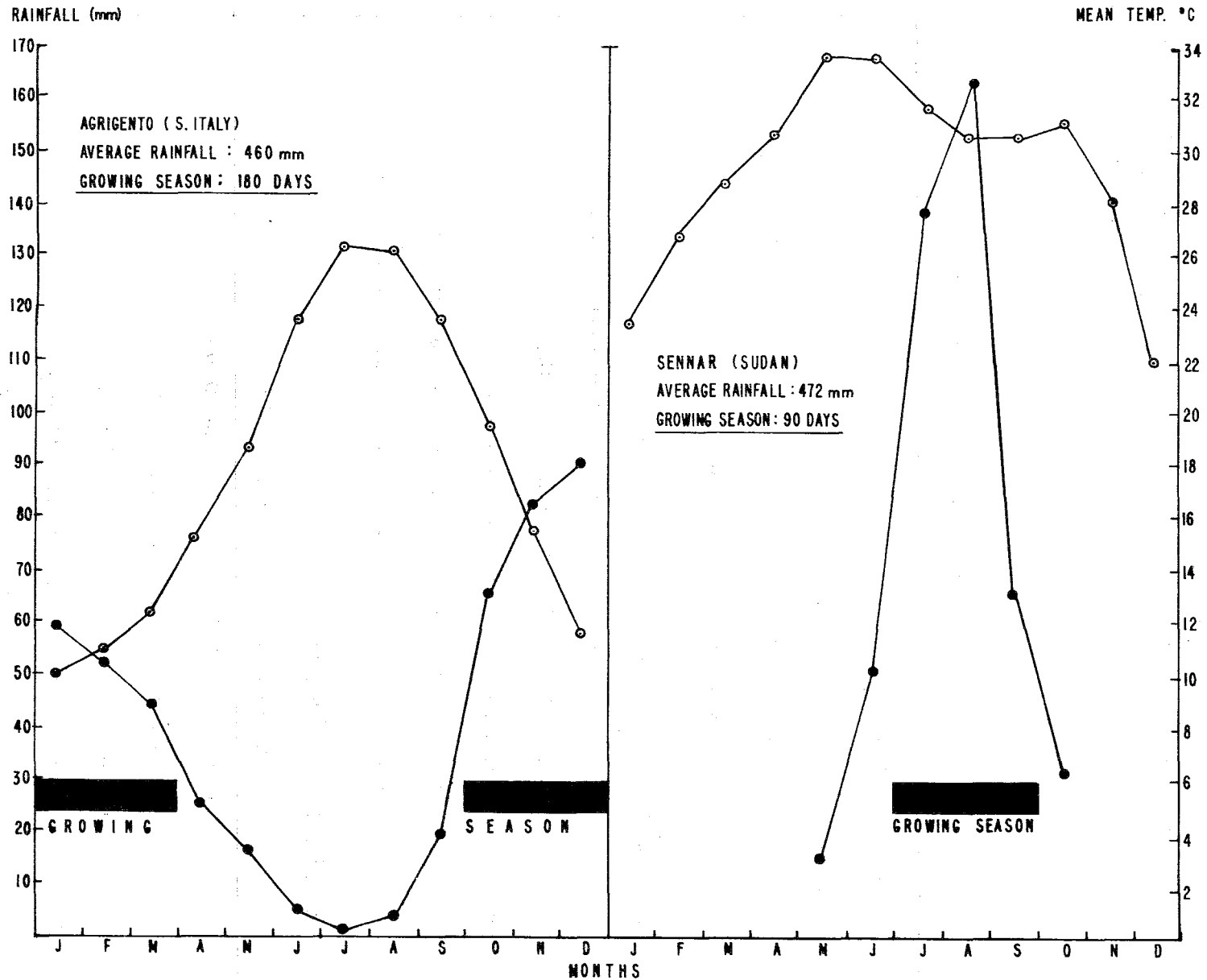


Figure 1. Comparison between the growing season in a temperate (left) and tropical (right) climate with same amount of rainfall

In the present paper, therefore, the identification of the boundary of the semi-arid tropics has been made on the basis of the agroclimatic determination of the length of the possible growing season for crops according to the water balance. This classification has had a practical application in several studies carried out on the agroclimatology of tropical zones /1, 2, 3, 4/. On this basis, the general characteristics and the boundaries of semi-arid tropics and also the main features of sub-zones are given in Table 1.

Table 1

Agroclimatic classification of the semi-arid tropics

GENERAL CHARACTERISTICS:

- Annual PET exceeds rainfall
- Rainy season occurs in summer
- Yearly mean temperature exceeds 18 deg C

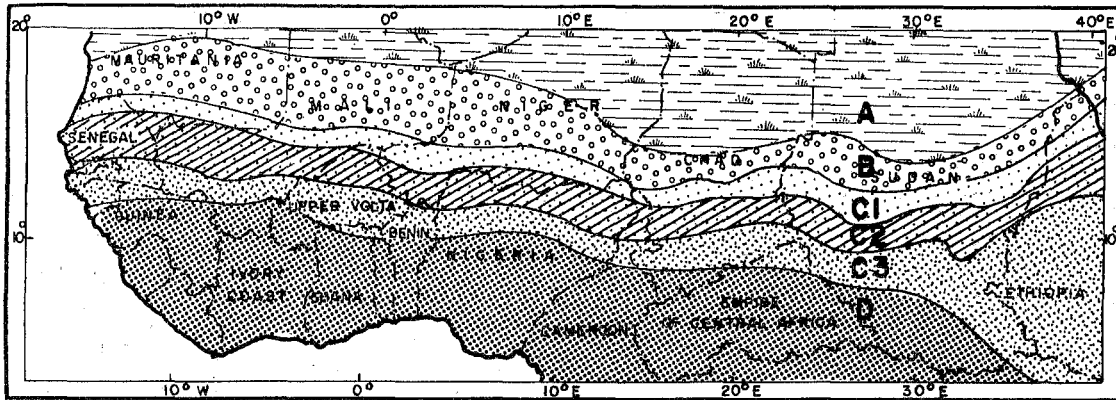
BOUNDARIES:

- Driest: - Possible growing season not shorter than 60 days
- Rainfall exceeds PET for not more than 10 days
- Wettest: - Possible growing season not longer than 200 days
- Rainfall should not exceed PET for more than 100 days
 - Rain pattern should not allow 2 crops in the same year

MAIN FEATURES OF SUB-ZONES:

- C.1 - Growing season between 60 and 100 days
- Rainfall exceeds PET for less than 60 days
- C.2 - Growing season between 100 and 160 days
- Rainfall exceeds PET for 60 to 100 days
- C.3 - Growing season between 160 and 200 days
- Rainfall exceeds PET for less than 100 days

Note: For the limits of other features of semi-arid areas of tropical Africa, see also Figures 2, 3 and 4.



- | | | |
|------------|------------------|-------------------|
| A - Desert | C1 - Semiarid I | C3 - Semiarid III |
| B - Arid | C2 - Semiarid II | D - Humid |

Figure 2. Agroclimatic zones of tropical Africa south of the Sahara

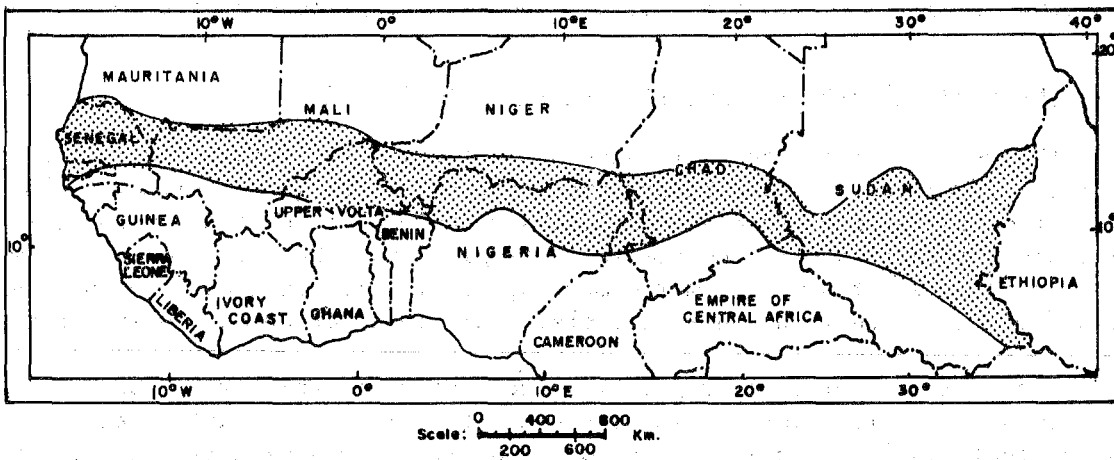


Figure 3. Limits of the zone in which rainfall exceeds PET for a number of days between 0 and 120

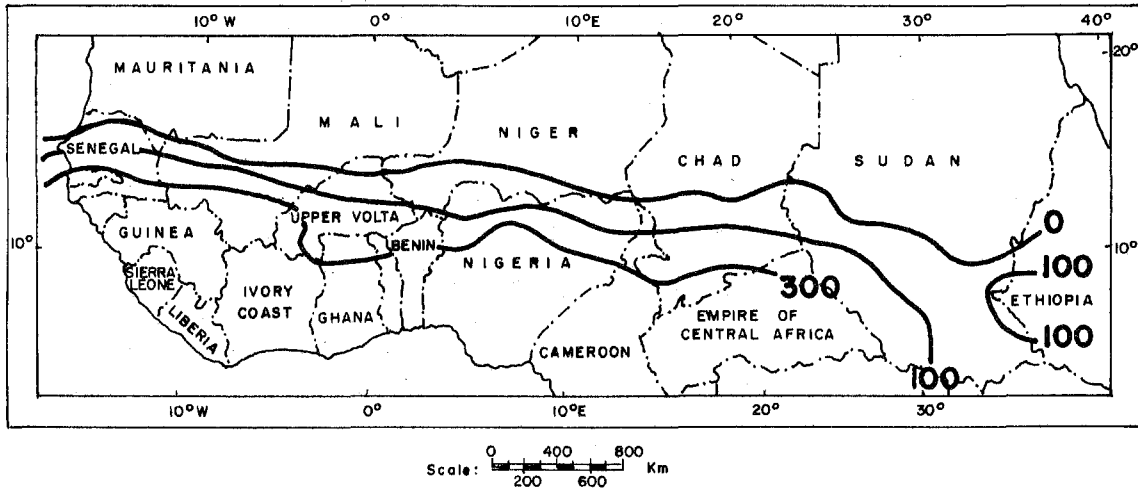


Figure 4. Water losses (mm)

In general, the drier boundary of the semi-arid zones lies in the transition zone between grazing lands and the areas with first, scattered settlements, where short-cycle crops are usually cultivated. In terms of rainfall, this limit runs approximately near values of 350 - 450 mm. The humid boundary, on the other hand, may be considered as the transitional area between uni- and bi-model rainfall régimes (see also 5), and may be included between the isohyets of 1 000 and 1 500 mm of annual rainfall, according to its distribution and the pattern of the rainy season.

2.2 Geographical distribution of the semi-arid tropics

The most important and extensive area of semi-arid tropics in the world lies in tropical Africa south of the Sahara (see Figure 2). Different climatic classifications for tropical Africa are given in Tables 2 and 3. Often it has been considered that the Sahel coincides with the semi-arid tropics, but the origin of the term (shore of the desert) gives it a more limited meaning, as the transitional zone between the desert and permanent settled lands (see also overview paper by Oguntoyinbo and Odingo).

The African semi-arid tropics include a belt, approximately 500 km wide in the western part and much more in the eastern part, from the Atlantic Ocean to the Ethiopian highlands in the east. They cover an area of approximately 4 million km².

An extended area with similar characteristics is present in India (Figure 5) and covers a surface of approximately 1.3 million km².

Finally, semi-arid tropical conditions are present in a rather narrow belt of the northern part of Australia. No comparably large areas of the Americas may be classified as semi-arid tropics.

Table 2

Climatological classifications

MEAN ANNUAL RAINFALL mm	KOEPPEN (1931)	THORNTHWAITE (1948)	AUBERVILLE (1949)	RODIER (1964)	
				METEOROLOGIQUE	HYDROLOGIQUE
0	DESERTIQUE BW	ARID	SAHARIEN	SAHARIEN	DESERTIQUE
100				SAHELIEN NORD	SUB-DESERTIQUE
200			STEPPIQUE BS	A'E	SAHELO-SAHARIEN
300	SAHELO-SOUDANIEN				
400	DE SAVANE AW	SEMI-ARID A'D	SOUDANO-GUINEEN	SOUDANIEN I	TROPICAL PUR
500					
600		DE MONSOON AM	HUMID A'B	SOUDANIEN II et III	TROPICAL DE TRANSITION
700	AU DESSOUS DE 8° - 9° LAT. N				
800		LIBERO-DAHOMEEEN	EQUATORIAL DE TRANSITION		
900	1 000				
1 100		1 200			
1 200	1 300				
1 300		1 400			
1 400	1 500				
1 500		1 600			
1 600	1 700				
1 700		1 800			
1 800	1 900				
1 900		2 000			
2 000					

Source [1]

Table 3
Landscape components

Mean Annual Rainfall mm	Domain	Physical landscape	Natural vegetation	Soils	Land use (irrigation excepted)		
					Animal rearing	Cultivation	
50	SAHARIEN	Stony, sandy desert, dunes	None except scattered plants in depressions	Lithosols	Large scale nomadism (~ 300 km)		
100			Widely scattered	Yermosols Regosols Dunes			Pastoralism with camels and sheep
200	SAHELIEN	Patches of dunes in eroded soils with depressions (bas-fonds)	Open steppe	Arensols Yermosols (spots of Gleysols) Solonchacks (Solonetz) Fluvisols	Nomadic transhumance (~150 km) - Pastoralism with camels and cattle	No diversification (Niébé, millet, short cycle groundnuts)	
300			Wooded steppe				Semi-sedentary pastoralism with camels and cattle
400			Temporary swamps				
500			Wooded savannah				
600	SOUDANIEN	Eroded slopes		Luvisols Fluvisols	Sedentary pastoralism	Little diversification (Millet, sorghum, groundnuts)	
700				Vertisols	Limit of endemic glossina		
900				Luvisols Gleysols			
1 100	GUINEEN			Nitosols Ferralosols		Wide diversification Long-cycle millets and sorghum, groundnuts, cotton	
1 300			Dense forest	Luvisols			
1 500							Rice (in heavy soils)

Source 1/

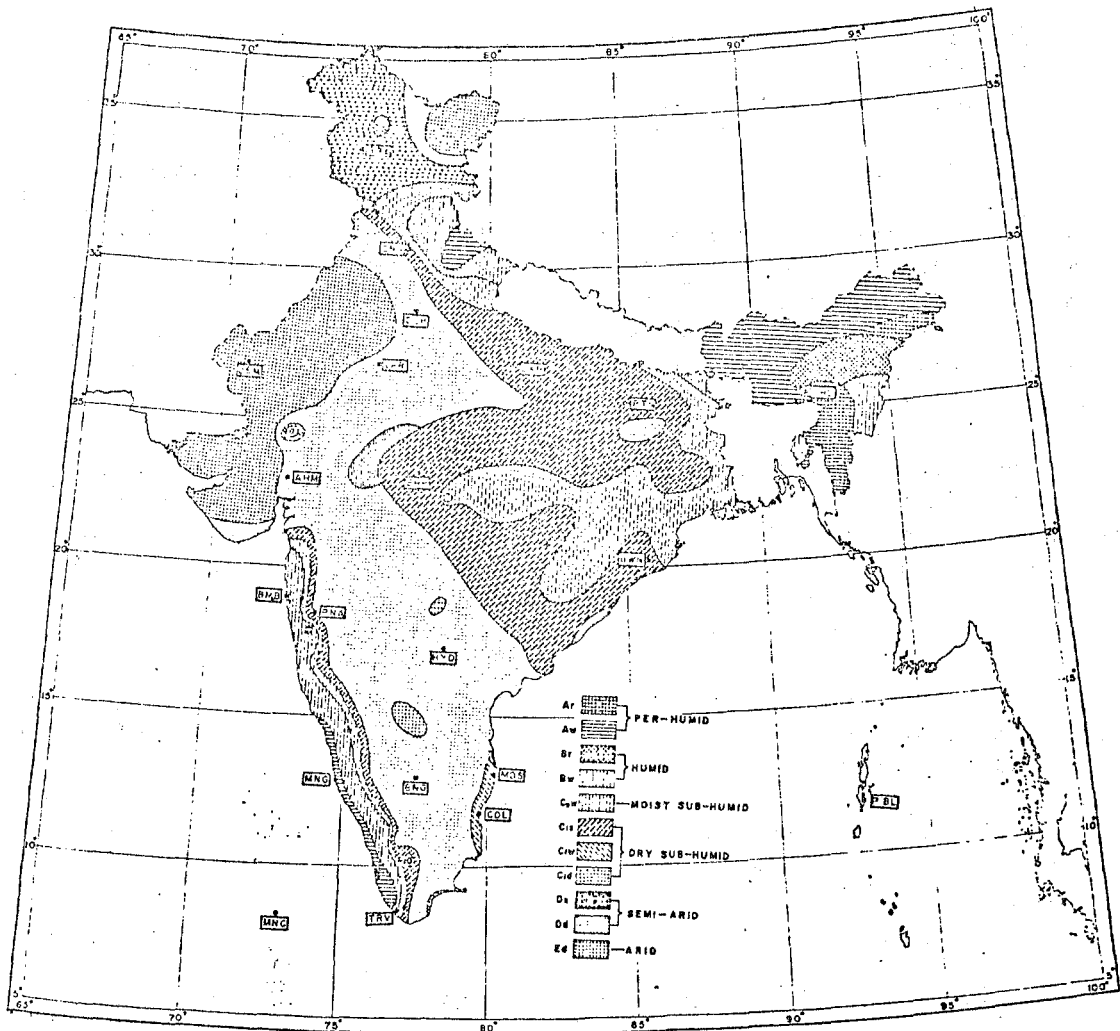


Figure 5. Agroclimatic zones of India. Source [4]

2.3 Land use and agricultural systems

A short summary of different kinds of land use in the semi-arid tropics of Africa may be found in [1] while, as far as India and other regions are concerned, it is possible to find extensive treatments in [6, 7]. Only the main features of land use and crop pattern having closer links with climate will be illustrated in the present report.

2.3.1 Crops and crop characteristics according to climate

In the zones of rain-fed agriculture the number of major crops is generally limited to sorghum, millet, maize, cowpea and sesame as food crops and cotton and groundnuts as cash crops. Other important crops, such as rice, sugarcane as well as wheat in wintertime, can only be cultivated where supplementary irrigation is available.

The above mentioned crops are widespread in the semi-arid tropics, but they show various adaptations to different ecological and climatic conditions. Among these, photosensitivity and length of life cycle appear the most important factors for the adaptation to diversified climatic conditions throughout the semi-arid tropics. Practically all the food crops mentioned above are photosensitive and the response may reach 10 minutes' variation in day length for some varieties of sorghum (Curtis /8/). A striking example of the adaptation of different varieties of sorghum to climate was found by Curtis /9/ and Bunting and Curtis /10/. The date of heading of such varieties is strictly related to the average date of the end of the humid period and not to that of a given year, showing that the natural mechanisms of selection allowed different ecotypes to adapt themselves to "more frequent" conditions of weather, irrespective of its variability.

Another important feature is the length of growing cycle. Going from more arid to more humid zones, the local varieties show life cycles which are close to the length of the period of water availability. So early varieties of millet or cowpea (60-90 days) may be found in the more arid areas (sub-zone C.1 of Table 1). Different varieties of sorghum have life cycles from 90-100 days to 14 months. The latter is found in particular boundary conditions of southern Sudan /11/.

The strict adaptation of crops to climate represents a mechanism to utilize better the concentrated water resources and to escape particularly unfavourable conditions. Timely flowering of sorghum just after the peak rains means that insect attacks (*Atherigonia* sp., see /5/) can be avoided. Furthermore, a common characteristic of many tropical crops is the sharp reduction in yield when sowing is retarded after the normal time. This phenomenon is probably linked with the photoperiodic mechanism cited above.

The above mentioned characteristics seem to indicate that tropical annual crops are well adapted to average conditions of weather, i.e., to climate, but are in some way very sensitive to its variability.

2.3.2 Land use

Agricultural systems in semi-arid tropics are clearly conditioned by the distribution of rains and the length of the period of water availability (Table 4 and Figure 6). In the more arid part (sub-zone C.1) the agricultural systems are very simple: four crops are usually cultivated (early millet, cowpea, sesame and, very seldom, early groundnuts). Fallows are very common and the fallow-crop ratio is rather high (3:1 or 4:1), even if social reasons such as increasing population pressure give rise to incorrect land management with a decrease of fallows and an increase of cultivated soils. The presence of a relatively high rate of fallows seems essential in the more arid zones because of the presence of diffuse animal rearing. The presence of cattle is important for the soil fertility and any decrease of fallow means a consequent decrease of fertility.

In such areas timely sowing is essential but the high variability of rainfall obliges farmers to make repeated sowings if unusually long dry spells occur after the first useful rain.

Table 4

Scheme of field operation
and crop development in semi-arid tropics

<u>Conditions</u>	<u>Traditional rain-fed agriculture</u> <u>Operations or crop phases</u>
Single first rain exceeding 10-15 mm	Soil preparation
Cumulated rainfall in one week or ten-day period of 30 mm or more	Sowing
Rains \gg PET	Vegetative development Flowering Weed control
Rains \ll PET	Beginning of ripening
Rains + soil reserves depleted	Full ripening Harvest

The humid part (sub-zone C.2) shows the greatest potential for agriculture. The crop diversification is high, rotation is common (cereals and leguminous species, or cotton and cereals), even if fallow (with or without animal rearing) is frequent. Mixed crops are also frequent [5]. In this area the lower variability of rain, as well as its higher total amount, allows farmers to make better programmes in soil management and in agricultural practices. Nevertheless, limitations to good yield may be caused by the high variability of the onset and end of rains, which may damage both sowings and ripening processes.

The boundary towards equatorial zones (sub-zone C.3) shows limitations due to excess rainfall, easy runoff and high seepage during peak rains. In this condition shifting cultivation is frequent and the fertility remains the main limiting factor, also because animal rearing tends to disappear owing to the frequency of animal diseases, such as trypanosomiasis.

In this zone, timely sowing becomes essential in order to utilize the limited amount of nitrogen fixed by soil bacteria in the first phases of the rainy season [12]. Another inconvenience, caused by the relatively high, though concentrated, amount of rains, is soil erosion which can be overcome through the use of fast-growing varieties that may cover the soil before heavy rains start.

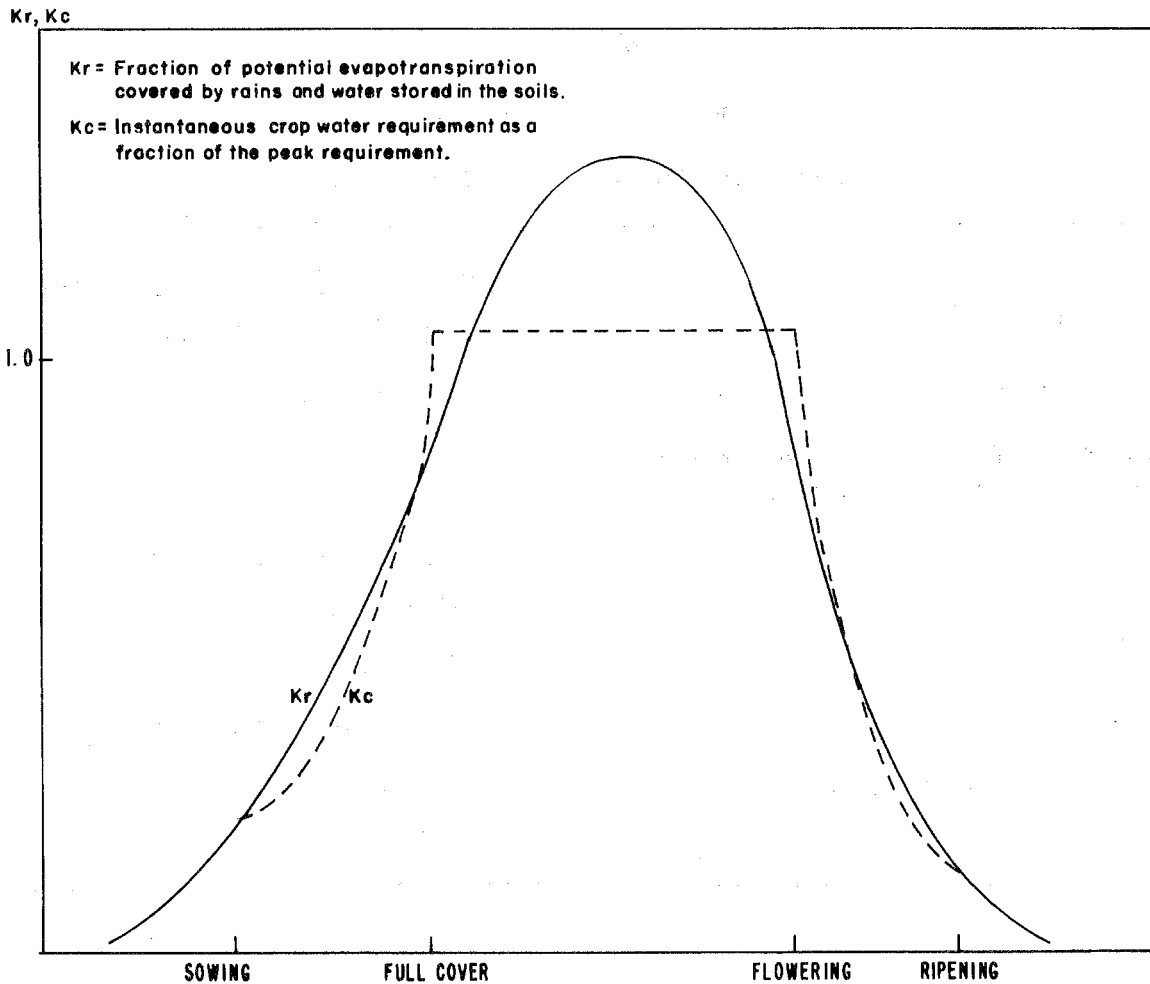


Figure 6. Comparison between the water availability and water requirements of crops throughout the rainy season

Although incomplete, these elements may show the extent of the impact of the climate on crop growth and land management in the semi-arid tropics. With this in mind, the discussion of the effect of variability will be easier to understand.

2.3.3 Irrigation and flood retreat cultivation

The cultivation of temperate crops such as wheat is only possible in the tropics in winter, i.e., during the dry season. On the other hand, some typical tropical crops such as rice or sugar-cane cannot be cultivated in semi-arid zones without supplementary water for irrigation. The adaptation of crop cycles to climate is the fundamental prerequisite for successful cultivation. As far as wheat is concerned, it is necessary to exploit the relatively cool months from November to March. Nevertheless heat waves in February may strongly decrease final yield through a disturbance of the final phases of ripening.

The same problem appears in irrigated areas with tropical crops. Flower fertilization may be prevented in rice by high temperatures and low humidity. On the other hand, the winter growth of irrigated sorghums may be stopped by night temperatures below 15 deg C.

Irrigation in the tropics, therefore, has great possibilities but climatic constraints should not be ignored, also bearing in mind the generally very high cost of irrigation water.

An important form of traditional agriculture, although limited in size, is the so-called flood retreat cultivation common along the main rivers of tropical Africa. Various crops, such as sorghum or cowpea or maize are cultivated on the low-lying areas along the watercourses just after the flooding. All phases of growth may be supported by the water stored in the soil during the flooding. This form of land use is strictly linked with the seasonal pattern of rains in the catchment area of the river concerned.

3. Climatic variability and agriculture

Section 2 showed, in summarized form, the strong connexions between crop growth and climate in the tropics. Of course, the variability of climate is crucial to the success or failure of crops and crop systems. This influence is, as mentioned before, much greater than elsewhere in the world.

3.1 Climatic variability - definition

The existence in the semi-arid tropics of two well-separated seasons does not permit a unified definition of climatic variability. During the dry season, the variability of climatic factors is very limited, whereas it is relatively high in summer /13/, see Figure 7.

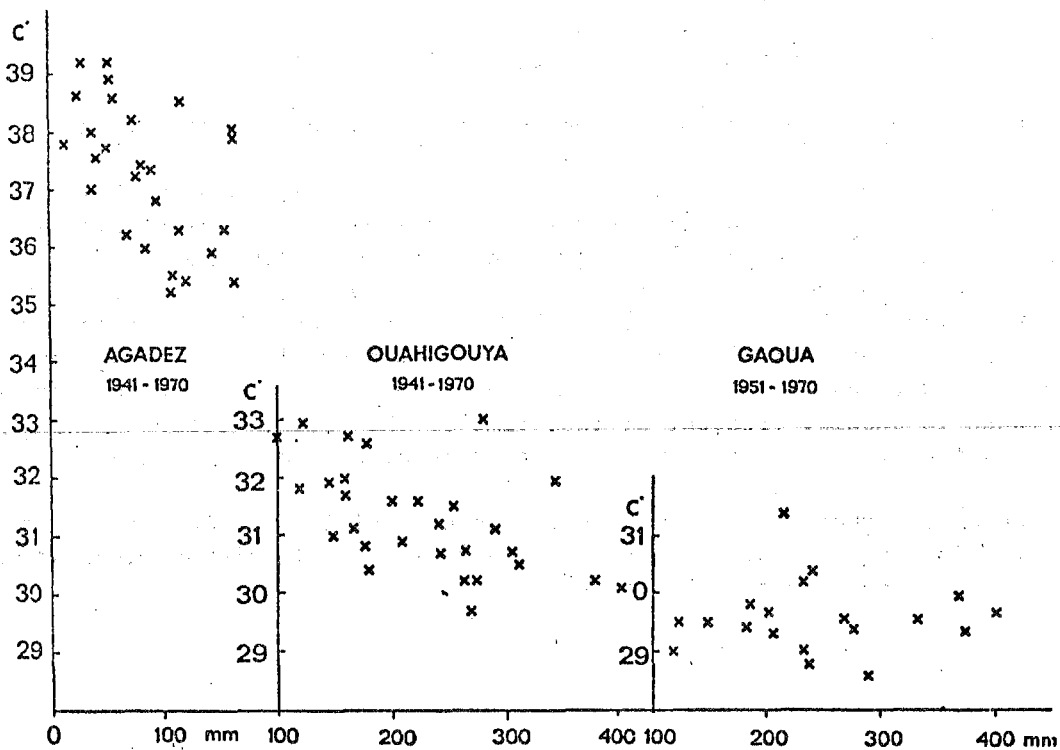


Figure 7. The scatter of average of maximum temperatures and average rainfall in August in different years. Source /1/

Furthermore, it has been demonstrated that mean air temperature during the rainy season is inversely related to the amount of rain and is independent of latitude. Even an agroclimatic element like PET does not show high variability. On an annual basis PET varies about 5 per cent from the average, whereas during the rainy months the departures may reach 12.5 per cent /13/. As far as rains are concerned, their variability is generally high and depends upon the amount of rain for the time interval taken into consideration as well as the mean level of annual rainfall.

In the present paper, therefore, the interannual variability of the rain pattern and its effect on water availability for crops will be utilized as the basic element for discussion of the consequences for rain-fed agriculture.

3.2 Rain-fed agriculture

The strict adaptation of crops and crop patterns to climate in the semi-arid tropics has been stressed in the preceding sections. Therefore, the first consideration which may be made is that, except in some particular situations (which will be discussed later), any variation in rain pattern, regardless of its direction may adversely influence the crops.

The main elements of the rain pattern whose variability may have a consistent impact on agricultural practices and crop development are the following:

- (a) Crop behaviour at the beginning and end of rainy season;
- (b) Duration and occurrence of dry spells;
- (c) The time-dependent variations of water balance.

3.2.1 The fluctuation of the occurrence of first and last "useful rains"

"First useful rain" here means the first rain in the season that allows farmers to start sowing /14/. One of the most critical periods of plant life is that just after sowing or emergence. In the tropics the sowing time for most crops takes place just after about 30 mm of rain has fallen in a ten-day period. In such conditions an equivalent of 0.4-0.5 PET for 7-10 days is assured. Nevertheless, given the limited storage of water in the soil at the beginning of the growing season, the occurrence of a dry spell longer than 7-10 days after sowing is extremely dangerous. Its occurrence is usually frequent at that time of the rainy season /14, 15/. Table 5 shows the distribution from month to month of wet spells at Zinder.

There are, therefore, two different aspects of the variability of rain patterns at that time: first, the date of the first useful rain and, secondly, the occurrence of dry spells after that date.

Table 5

Monthly mean number of wet spells of different lengths and percentage of rainy days they contained during the months of the rainy season

ZINDER 1931-1960

	Length of spell - days					
	1	2	3	4-5	6-8	8
May	2.5 70%	0.5 24%	0.1 6%			
June	4.2 68%	0.7 21%	0.2 11%			
July	5.5 50%	1.1 20%	0.6 15%	0.2 8%	0.1 7%	
August	4.6 33%	1.4 21%	0.8 17%	0.7 21%	0.1 6%	0.03 2%
September	4.2 58%	1.1 28%	0.3 11%	0.1 8%		
October	0.5 70%	0.1 17%	0.03 13%			

Source 15/

Benoit 14/ has shown that in northern Nigeria the variability of sowing time is extremely high, a feature that is demonstrated in Table 6. For 2:10 probability of occurrence, the possible sowing time falls in a period of 34-42 days, irrespective of the average rainfall of the area concerned. The consequences of such variability are very important for most crops, Andrews 12/ showed that late sowings decreased yields of sorghum and that each week of delay induced about 12.5 per cent of decrease of final grain yield. The adverse effect of late sowing on yield of sorghum was also found in semi-arid tropical Australia 16/.

The importance of the timely occurrence of sowing has been recognized by ancient traditional agriculture, mainly in the more arid zones. The farmers, who live in the region of the Dallols, in central Niger (with approximately 600 mm annual rainfall - agroclimatic zone C.1) customarily store different varieties of seeds of millet, some of them suitable for retarded sowing in the years of maximum delay of rains. One such variety is called by the very expressive name of "last hope". The late varieties have, of course, different lengths of growing cycles and different responses to photoperiod.

Table 6

Start of the growing season in specific years

Year	Mokwa 09.37°N 05.04°E	Samaru 11.11°N 07.38°E	Kano 12.03°N 08.32°E
1951	May 13	May 14	June 16
1952	May 14	May 10	May 16
1953	April 28	May 7	May 14
1954	April 19*	May 4*	June 19
1955	April 20	May 28	May 31
1956	May 16	May 22	June 16*
1957	May 8	May 4	May 20*
1958	April 15*	May 21	June 3*
1959	May 14*	May 14	July 1*
1960	May 1*	May 26	June 18*
1961	May 21*	June 1	June 26*
1962	April 29	May 22	June 3
1963	May 2	May 20	June 16
1964	April 30	May 27	May 27
1965	June 1	May 29	June 6
1966	May 14*	April 26	May 21
1967	April 18	May 21	June 14
1968	April 13	May 15*	May 19
1969	May 4	May 27	June 10
1970	May 16	May 15*	July 1*
1971	May 13	June 29*	July 3
1972	May 21*	May 23*	May 28
1973	May 30*	June 23	July 12
1974	May 3	June 24	July 2
1975	April 23	April 18	June 14
Mean	May 6	May 21	June 10
S.d.	13.4 days	16.6 days	16.4 days

* = Possibility of planting earlier in given year, but dry spell of 6 to 10 days occurred between earlier date and given date for start of growing season.

Source /14/

It is important to point out also that soil preparation usually takes place after the first rain of 10-15 mm. It is therefore essential that the interval between such rain and the suitable conditions for sowing time is sufficiently long to allow farmers to make appropriate operations on all cultivable surfaces. The shortening of this period below the average is always detrimental.

Variations in the end of the rainy season are also wide, even if the retreat of the Intertropical Discontinuity (ITD) is usually faster than its advance. If humid conditions ($R \gg PET$) are prolonged beyond the normal, ripening may be adversely affected; attacks of insects are much more frequent /5 - 15/. Birds (e.g., Quelea quelea) also represent a higher danger in years with retarded retreat of the ITD.

Drier conditions at the end of the season, on the other hand, mean more difficult grain filling and yields tend to be lower. This depends, however, upon the soil conditions and the trend of the rainy season before that time. In fact, good soil water storage may help crops to overcome dry periods at the end of the rains.

3.2.2 Importance of dry and humid spells

The distribution throughout the rainy season, rather than the total amount of rainfall, is of great importance in determining the final yield. Joshi and Kabaria /17/ found in Guaiaret, India, that final yield of groundnuts was significantly and positively related only to the amount of rain during the period from the initiation of flowering to full pegging. Each mm of rain accounted for 3.27 kg/ha of final yield. Several similar results may be found in the literature as far as tropical African and Indian semi-arid zones are concerned.

The occurrence of dry spells, therefore, has to be seen in different lights according to the time of occurrence, and the length of the spell and the mean rainfall of the area concerned (see Table 7 and Figure 8). The increased frequency of dry spells, however (as occurred during the Sahelian drought of 1969-73), is always dangerous, in more arid zones (sub-zone C.1), where the soil water storage is usually limited.

In more humid zones (C.2 or C.3) the effect of increased numbers of dry spells during the rainy season does not necessarily imply certain damage for plant growth. The peak months (usually August and early September) normally show excess rainfall, heavy runoff and seepage and reduced levels of radiation. The reduction of rains and increase of dry spells may be beneficial for crops through a reduced leaching of nutrients in the soil, an increase of photosynthetic processes, etc.

In a general way, however, the beneficial or detrimental variation of the length of dry spells may also be determined by soil conditions. Dark clay soils of tropical regions, for instance, are more fertile, but their permeability is low and they are subjected to waterlogging. Longer dry spells may permit easier penetration of water into the soil, the opportunity for surface tillage, weed control, etc. Sandy soils with low water holding capacity and higher permeability do not benefit from prolonged dry spells.

Table 7

Effect of increasing length of dry spells
according to the time of rainy season

Rainfall regimes	Sub-zones		
	C.1	C.2	C.3
Beginning	Always negative for seedlings and first phases of growth		
Increasing	Negative	Negative or indifferent	Indifferent
Peak	Negative	Indifferent*	Positive
Decreasing	Negative	Indifferent	Indifferent
End	Negative	Negative	Indifferent

* or positive in clay soils

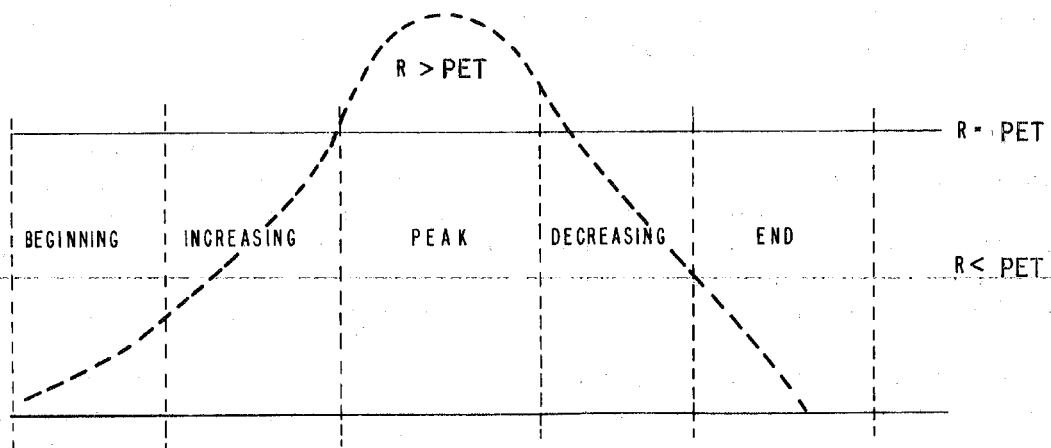


Figure 8. The pattern of water availability in semi-arid tropics

3.2.3 Pattern of the water balance

The final yield of a crop may be considered as the result of all favourable and unfavourable conditions during its life. The quantitative evaluation of the whole water balance throughout the growing season seems essential for this in order to explain the final results. Furthermore, this kind of analysis may be carried out on a large area basis and over a series of years in order to understand the relations between the variations of climate and crop growth and production. This kind of analysis, on the other hand, may give an indication of the agroclimatic fragility of an agrosystem, particularly when the environmental conditions are less favourable (as in sub-zone C.1).

To date, this analysis has been attempted for the whole semi-arid belt of Mali, Upper Volta and Niger for the year 1972, the worst of the recent period of Sahelian drought (1969-73). In this case the identification of the agroclimatic parameters of the sub-zones, as described in Section 2.1 (Table 1), has been carried out.

From Figures 9, 10 and 11 it may be seen that in the year 1972 the agroclimatic zones underwent a southward shift of about 150-200 km. Furthermore, the following aspects have been emphasized:

- (a) The sub-zone C.1 practically disappeared from its average position;
- (b) In a rather wide belt, although the possible growing season was close to the average for the zone C.1, no period with $R \geq PET$ occurred. It seems to be the most important element in explaining the crop failure of 1972.
- (c) The conditions and the position of the more humid sub-zone (C.3) was not greatly different from the normal.

The year-by-year analysis of the shifting of the agroclimatic zones, undertaken on the basis of water balance, may permit an easier understanding of the effect of climatic variability on agriculture on a regional basis.

3.2.4 Variability of annual rainfall and yield

Many attempts have been made to discover simple or multiple correlations between annual rainfall and yield. Davy, Mattei and Solomon ^[1] found that in some departments of Niger the yields were related to annual rainfall through a relation of a parabolic type (Figure 12), with maximum yield at the same values below the average. This kind of relation, however, tends to be much clearer and more significant in the more arid areas, where water is almost always the limiting factor for growth; where rains are more abundant the relation with yield tends to disappear for different reasons. One of them is the distribution of rain throughout the rainy season (see also Section 3.2.3). On the other hand, in many countries the yield data available are very scanty and usually refer to the whole country.

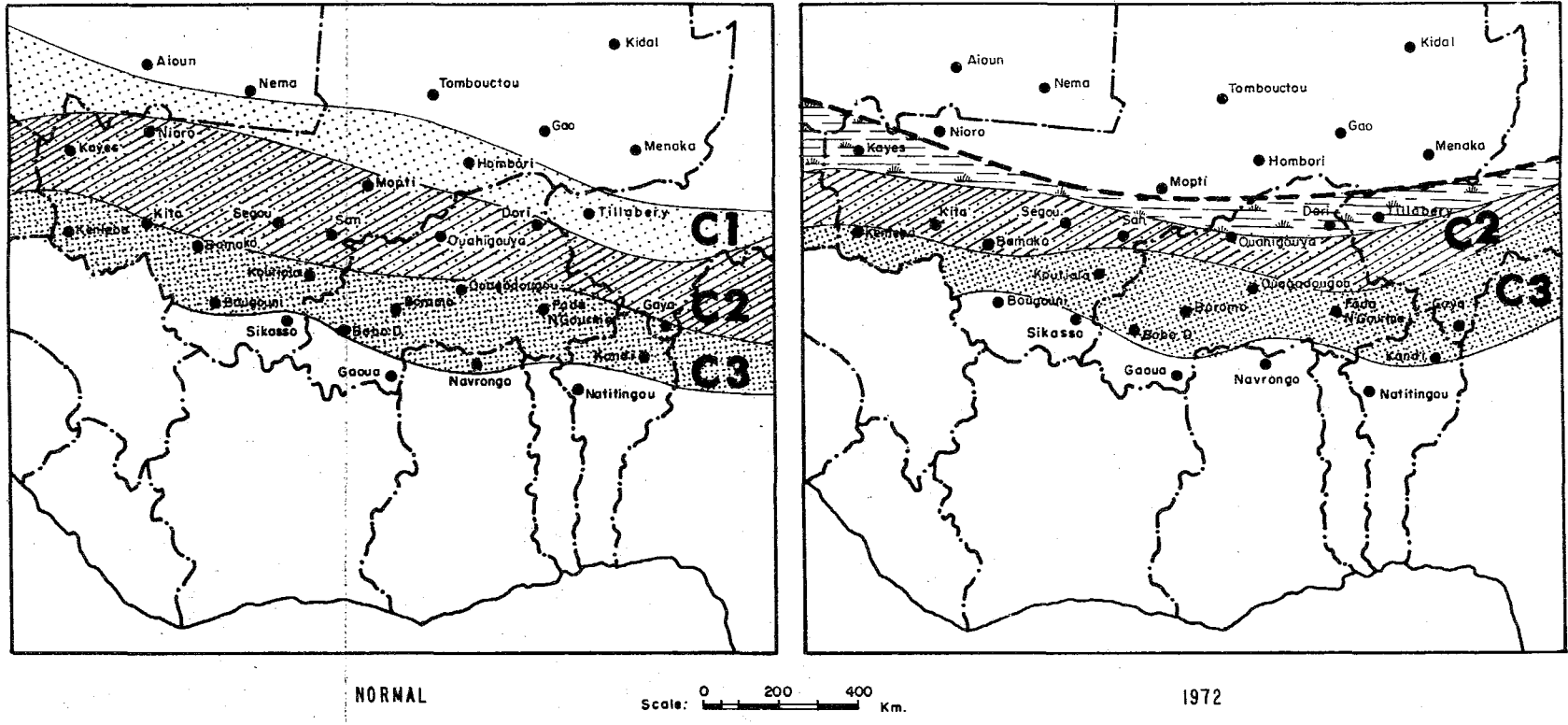


Figure 9. Agroclimatic zones of Mali and Upper Volta

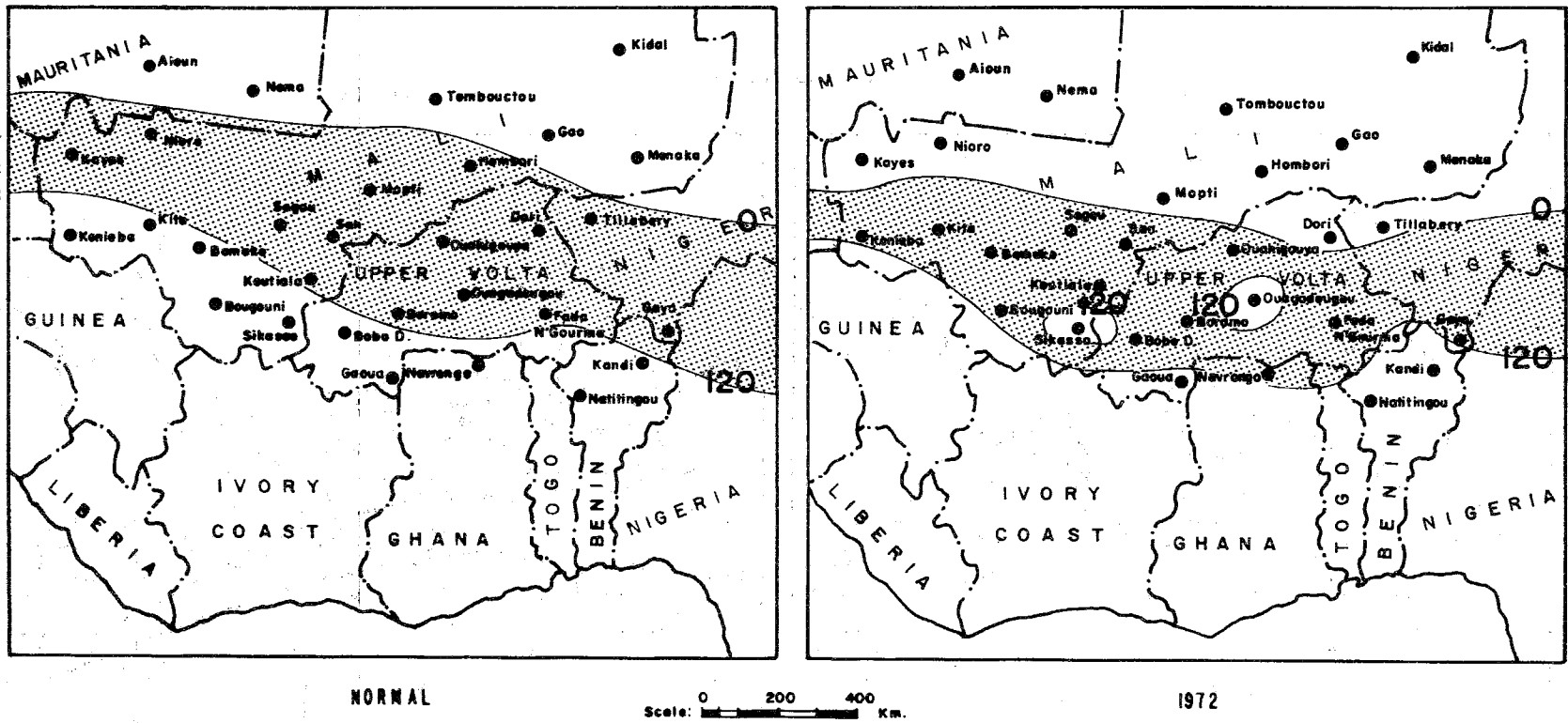


Figure 10. Limits of the zone in which rainfall exceeds PET for a number of days between 0 and 120

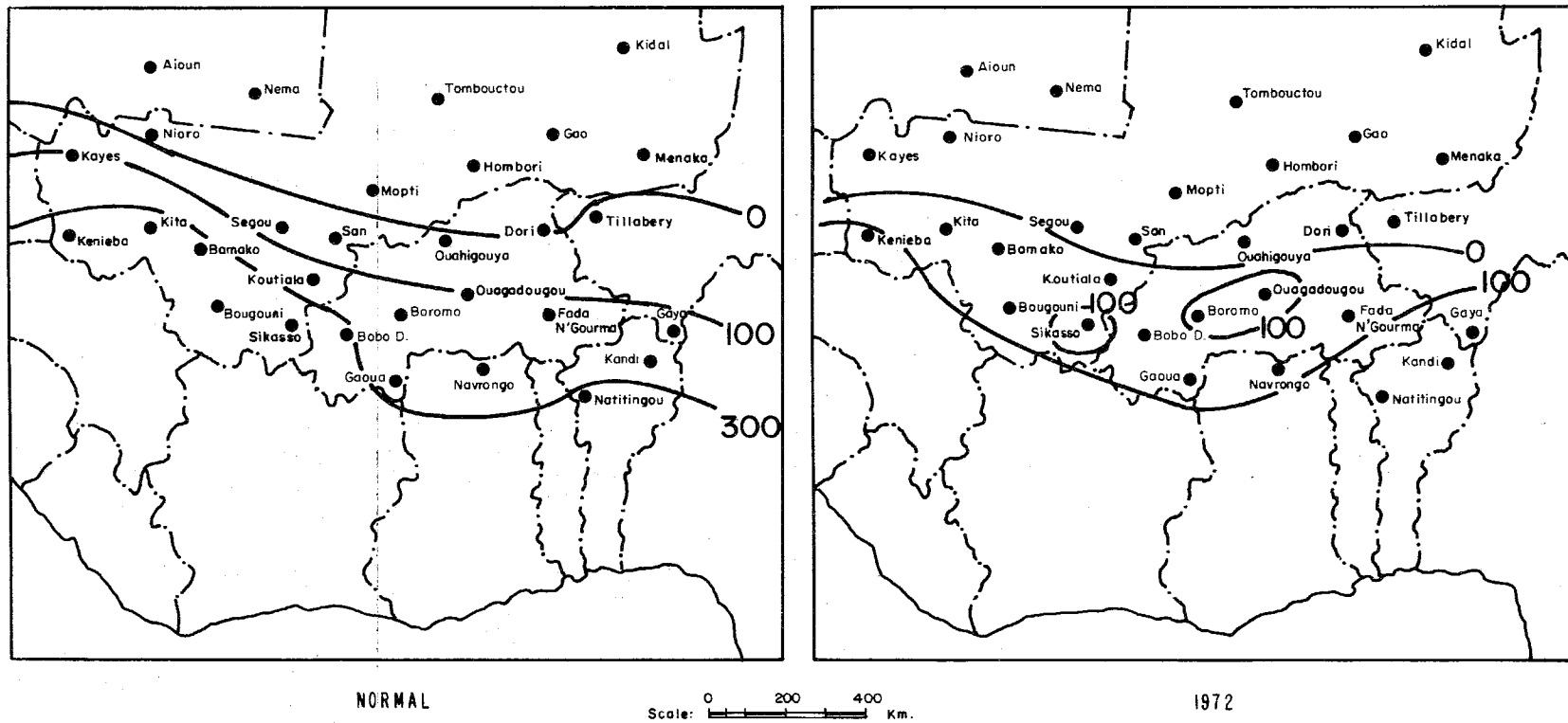


Figure 11. Water Losses (mm)

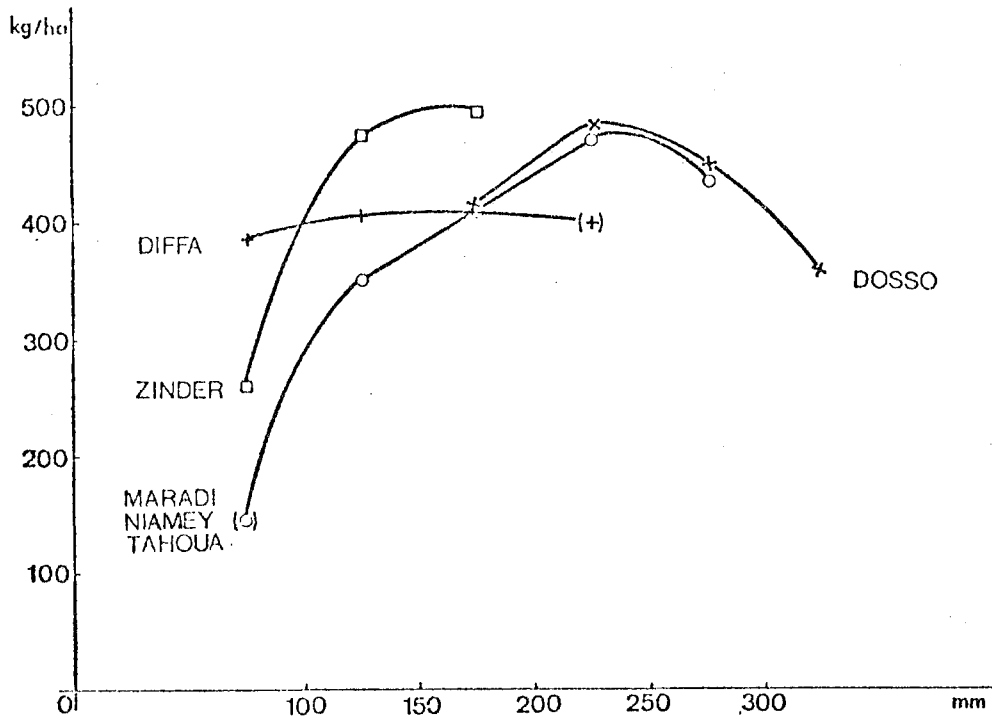


Figure 12. Relationships between average total rainfall from April to July and yield of millet in different provinces of Niger
Source [1]

The national statistics, therefore, are not easily manageable for the evaluation of the effect of climate on yield and production. It appears possible only in certain cases, as for the above-mentioned data from Niger and for the case of groundnuts in Senegal (see Figures 13 and 14). Here it clearly appears that total rains may have a positive or negative effect on yield, according to the general characteristics of climate and the amount of rain itself.

It is necessary to point out, however, that this kind of result from one area cannot easily be transferred to another area with different agroclimatic characteristics, even inside the belt of the semi-arid tropics, since local varieties with different physiological and ecological adaptations to climate react differently, as shown in the preceding Section 2.2.

It can be concluded that adequate knowledge of the impact of climatic variability of agriculture cannot be acquired through the rough analysis of the total annual rainfall, irrespective of the location, crops, water balance analysis, etc.

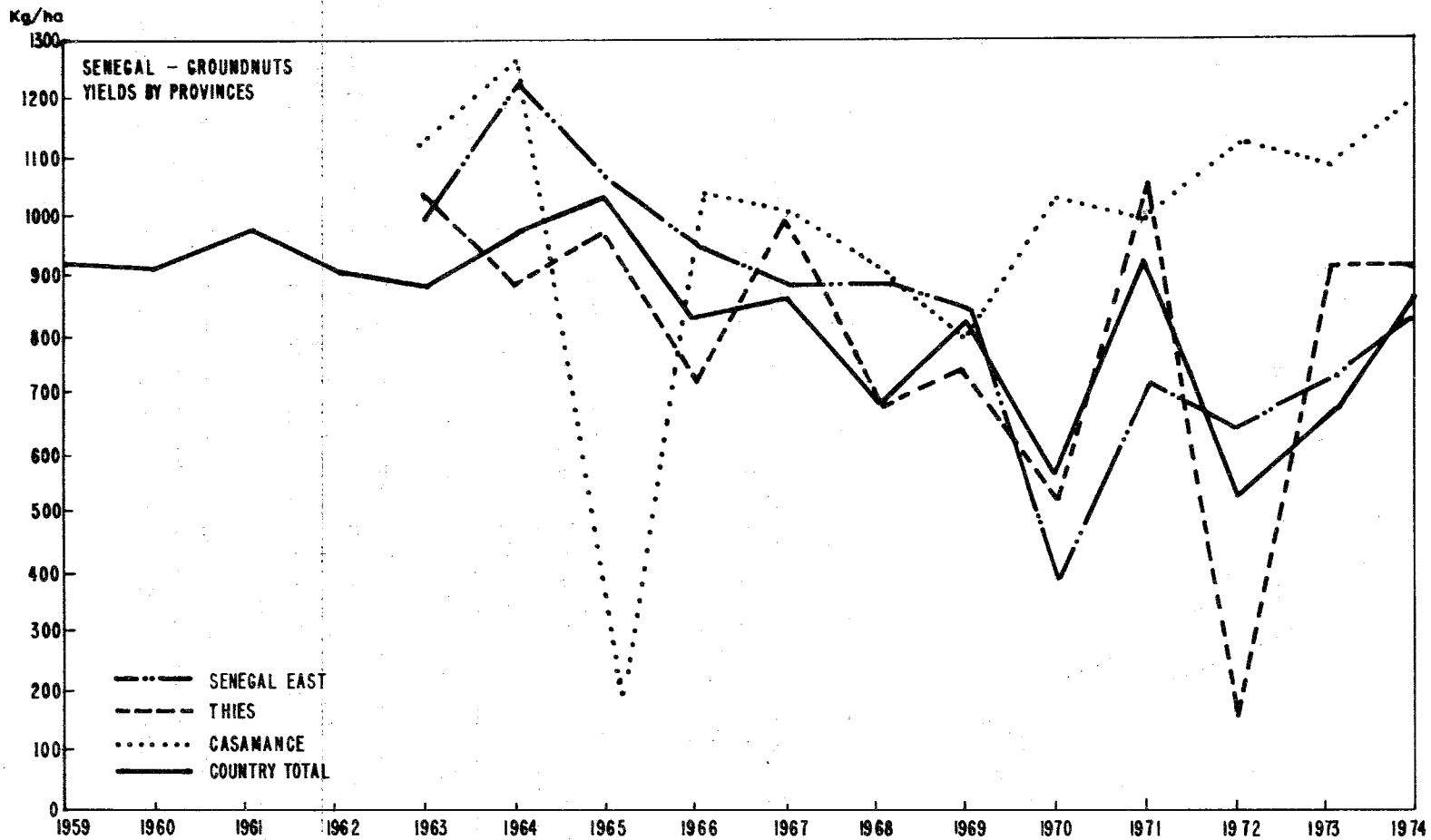


Figure 13. The inter-annual variation of yields of groundnuts in different provinces of Senegal

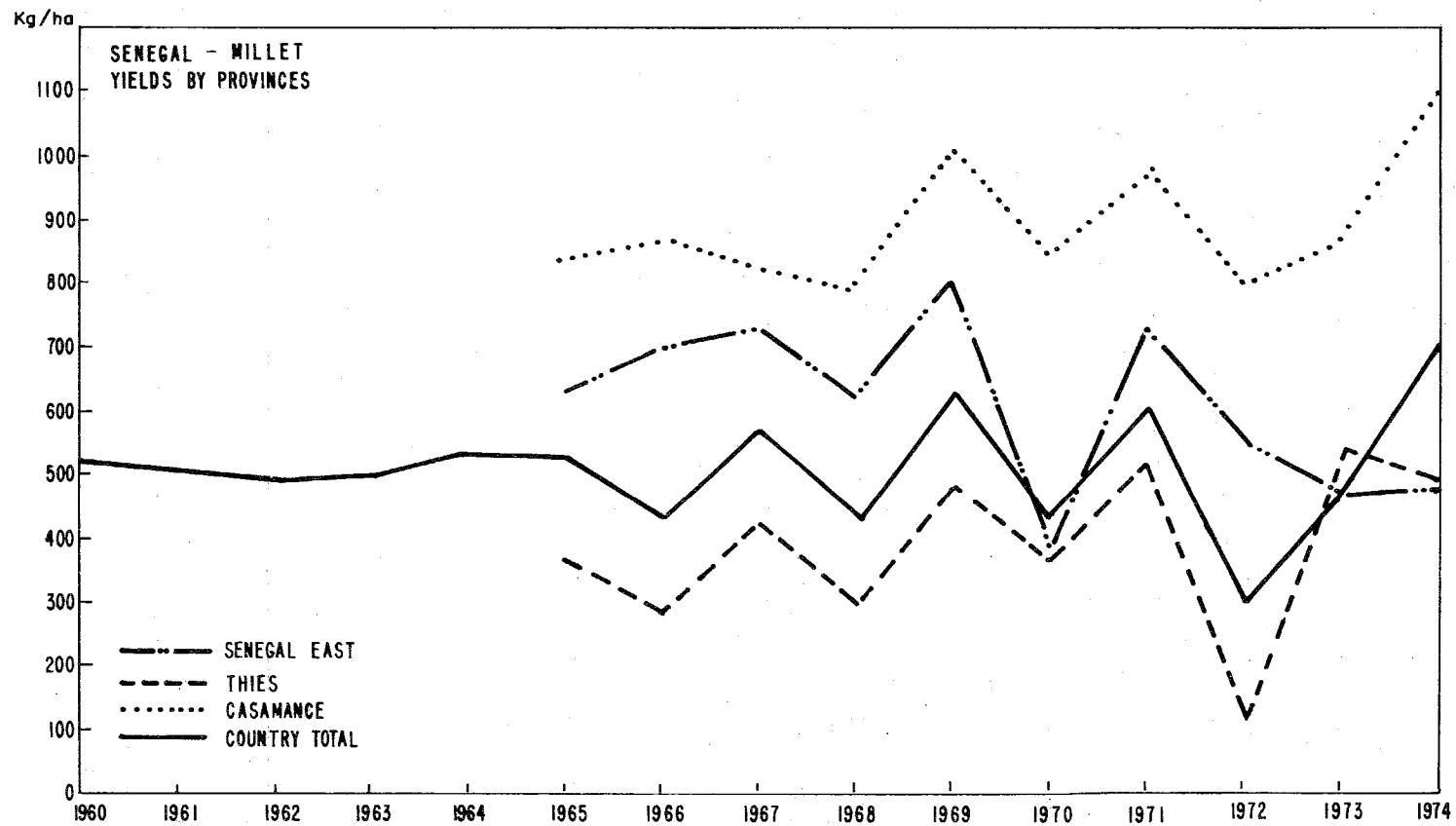


Figure 14. The inter-annual variations of yields of millet in different provinces of Senegal

3.3 Flood retreat crops and climatic variability

As mentioned in Section 2.3.3, the cultivation of soils close to river beds which are periodically subjected to flooding is a common practice in tropical semi-arid Africa. Although the total area involved represents only a small fraction of the total, this kind of agriculture has great economic importance for the people living along the river courses.

Obviously the extent of flood-retreat crops is greatly influenced by the peak flow rate and its duration, that is to say, by the amount of rains in the catchment basin of the river concerned. There are very few data regarding the year-by-year variations of the acreage of flood retreat cultivation. It has been calculated /18/ that the cultivated areas along the Senegal river during the drought of 1970-73 sharply decreased from an average of 150 000 ha to 100-110 000 ha in 1970 and 1971 and to only 15 000 ha in 1972. Furthermore, in the internal delta of the Niger River, the cultivation of rice on flooded soils only reached 5 000 ha in 1972, as against 40-50 000 ha in an average year.

The inter-annual variability of average river flows and peak flood is very high in tropical Africa, as may be seen in Figure 15 and Table 8, and consequently it may be suspected that the possible surfaces suitable for cultivation are subject to consistent variations in different years. However, the increase of possible surfaces during wet years should not increase proportionally to river flow, since physical obstacles such as river embankments limit the expansion of the river. Furthermore, social and organizational problems of the people living in these areas should also prevent too ample variations of cultivated surfaces during wetter years.

It may therefore be concluded that the variability towards drier years will influence the flood retreat cultivation to a greater and more negative extent than that tending towards more humid conditions.

The main obstacle to a more detailed analysis of this aspect is the scarcity of data. Today an evaluation of possible surfaces under cultivation along river beds may be carried out through the utilization of remote sensing techniques. Analysis of the data will greatly improve understanding of the relations existing between rains in the catchment areas, river flows and the surface of flood retreat crops. Timely analysis will also permit the forecasting of possible surfaces of cultivation, which appears of great economic significance.

3.4 Irrigated areas

In the tropics irrigation is usually utilized for winter crops unable to grow in summer, for the cultivation of rice, sugar-cane, cash crops and, finally, to supplement insufficient rain water. The most important climatic factor influencing crop growth in this case is temperature, which can positively or negatively influence growth.

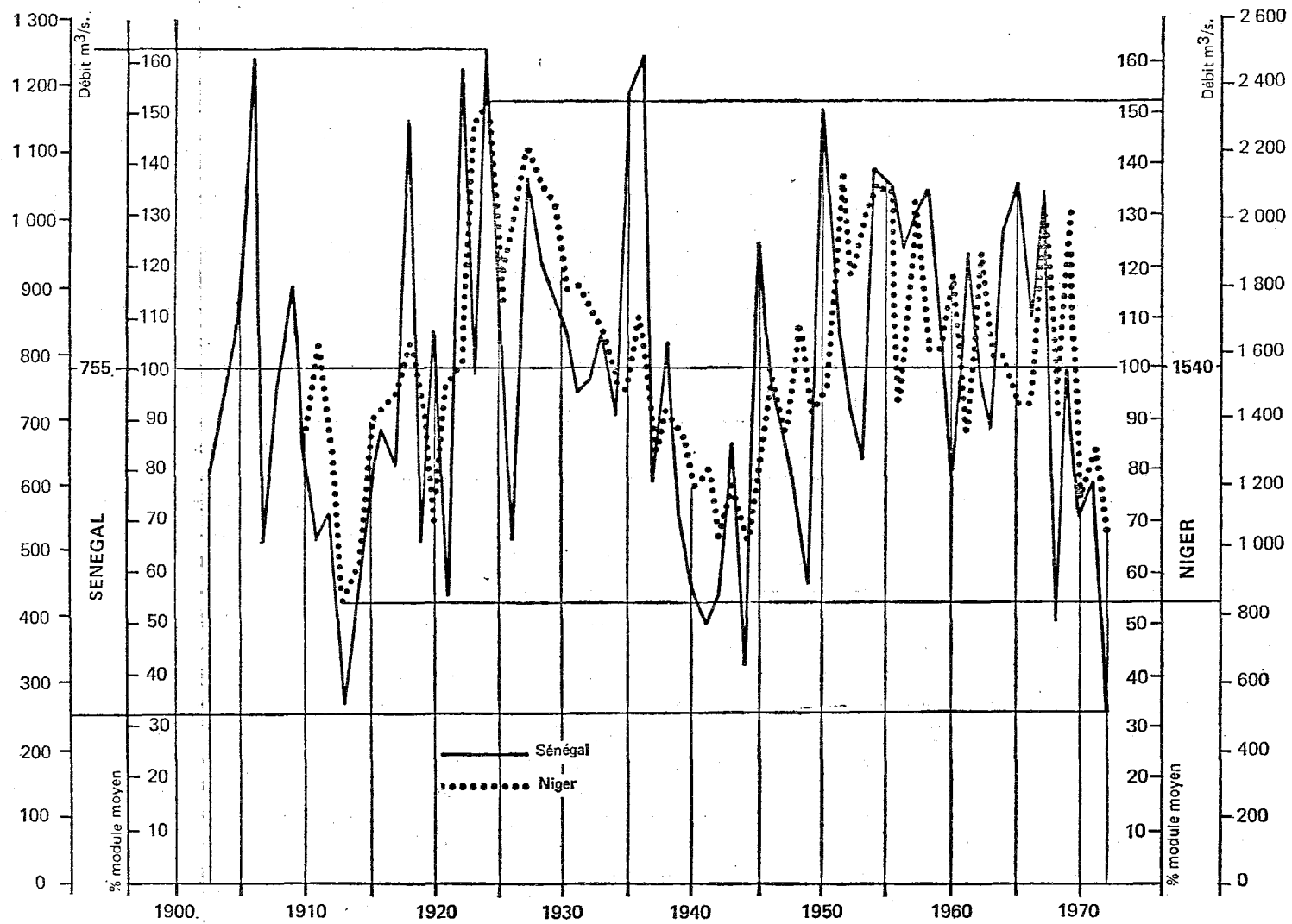


Figure 15. Inter-annual variations of Rivers Niger at Bakel and Senegal at Koulikoro
 Source 18

Table 8

The flows of different rivers in the Sahelian region -
Averages and 1972 values

Rivière	Station	Crue *		Module *		Etiage *	
		Moyenne *	1972	Moyen *	1972	Moyen*	1972
Sénégal	Bakel	4 770	1 430	764	264	2.3	0.25
Niger	Koulikoro	6 260	3 680	1 540	1 080	46.6	16
Niger	Diré	2 330	1 760	-	-	63.3	22
Niger	Niamey	1 860	1 560	1 010	647	75.6	2.5
Sirba	Garbé-Kouro	198	124	20.6	5.96	0	0
Maggia	Tsernaoua	36	40	1.34	0.88	0	0
Komadougou	Ouékourou	32.2	26.3	14.3	7.8	0	0
Volta Noire	Nwo Kay	105	48.9	37.1	17.2	5.9	3.5
Comoë	Karfi-Guela	104	16.6	6.9	3.8	-	-
Chari	N'Djaména	3 540	1 430	1 280	578	163	48
Logone	Laï	2 550	964	506	241	48.4	25
Logone	Moundou	2 110	996	390	215	29.3	12
Sanages	Edéa	-	-	2 070	1 440	-	-
Sangha	Ouessou	-	-	1 800	1 270	-	-
Oubangui	Bangui	10 500	9 200	-	-	-	-

* Moyen(ne) = Average, Crue = High-water, Module = Modulus, Etiage = Low-water Source 18/

The occurrence of cold or hot waves late in winter may give rise to various difficulties for some crops. On the other hand, timely sowing, essential for some temperate crops such as wheat, may be retarded by a prolonged hot season in autumn. The variability in this case should be evaluated above all as regards the frequency of occurrence of low temperatures or the anticipated start of the hot season late in winter (February-March). The cultivation of wheat, which is assuming more and more importance in irrigated schemes in the tropics, needs relatively cool weather for three months (December-February). A tendency towards higher temperatures decreases wheat yield.

On the other hand, the occurrence of cold waves in February may reduce the growth of some tropical crops under irrigation, such as sorghum.

Finally, it should be mentioned that variations of temperature induce variation in evapotranspiration in the same direction. It is not necessary to discuss other climatic factors such as solar radiation and air humidity, which are fairly constant during the dry season in the tropics.

4. Conclusions

As discussed in earlier sections, the traditional rain-fed agriculture of the semi-arid tropics shows a natural adaptation to average conditions and a relatively high fragility with increasing variability of the rain pattern; average yields are generally low and are lower than in extra-tropical or sub-tropical environments with similar climatic characteristics. The reasons for such low yield are numerous, but among them should be mentioned the low suitability of crops and agricultural systems to variability of climate. This means that even a relatively limited departure from the average climatic conditions may have an adverse effect on yields.

In another paper presented to this Conference (McQuigg 19/) the author, while discussing agricultural systems in temperate climates, states: "The current grain-producing systems of the world are still highly sensitive to the occurrence of large climatic anomalies". This statement refers to agricultural systems already developed and with a high technological input.

In the semi-arid tropics the constraints of climate are generally more severe than in temperate zones and variability generally tends to worsen the conditions for crop growth. On the other hand, the level of technology is extremely limited, even absent, and crops and cropping systems are generally at the mercy of the weather, the possible interventions being extremely limited. It follows that average yields are low in the tropics and often the anomalies of weather give rise to great variations in yield.

4.1 Consequences of variability

The tendency towards drier or wetter climate leads to several consequences for the agroclimate and for agricultural activities which are summarized in Tables 9, 10 and 11. The effect of such a tendency, however, is not uniform in all semi-arid tropics since in the more arid areas (sub-zone C.1) the main constraint is normally the limited amount of water and wetter years have generally a positive effect. Where rainfall is usually higher (zone C.2 and C.3), the tendency towards drier conditions may lead to both positive and negative effects. In fact, the concentration of rain

in a short period, within a single month (usually August) which accounts for more than 30 per cent of the total rainfall, represents an unfavourable condition for the stability of agrosystems. The decrease of the August: annual rainfall ratio has certainly a beneficial effect even if a decrease in total rains may take place. On the other hand, too high a variability at the onset of the rains may be negative for the establishment of good crop stands.

Table 9

Consequences of climatic variability for agroclimate

Tendency towards:	
<u>Drier climate</u>	<u>Wetter climate</u>
- Longer dry spells with possible shortage of water mainly in the first and final parts of the rainy season	- Lower air temperatures
- Higher temperatures (mainly daily maxima)	- Lower solar radiation
- Higher solar radiation	- Greater water availability
- Higher PET	- Higher soil leaching
	- Higher soil erosion

Moreover, it is important to underline the negative effects of persistence, which worsens the agrosystem's instability. In fact, a series of adverse years has a cumulative effect which is mainly due to the changes in the behaviour of rural communities. Among them may be mentioned migrations, tendency of nomads to settle in safer areas, loss of food reserves, etc.

4.2 Overcoming climatic variability

Overcoming the variability of climate appears to be essential for the progress of semi-arid tropical agriculture. It is clear that climatic variability has a negative impact that may be partially overcome through the progressive improvement of the present level of technology. This statement does not intend to suggest the immediate and wholesale introduction of new technologies in tropical agriculture.

Table 10

Consequences of climatic variability for agriculture

Tendency towards:	
<u>Drier climate</u>	<u>Wetter climate</u>
<p><u>In the zone C.1</u>, no positive consequences since water is always a limiting factor</p> <p><u>Neg.</u> - Unsuccessful and repeated sowings</p> <ul style="list-style-type: none">- Limited growth- Insufficient grain filling- Yield reduction- Greater soil erosion during dry season- Damage of natural vegetation- Decrease in animal stocking carrying capacity of pasturelands <p><u>In the zones C.2 and C.3</u> moderate decrease of rains implies:</p> <p><u>Pos.</u> - Less soil leaching</p> <ul style="list-style-type: none">- Less danger of waterlogging- Less danger of diseases at ripening stages <p><u>Neg.</u> - Higher risk of failure at sowing</p> <ul style="list-style-type: none">- Higher risk of decrease of grain filling- Negative effects of higher temperatures on some crops (ground-nuts, cowpea)	<p><u>In the zone C.1</u>, it is always positive except in the case of increasing intensity of single showers (soil erosion may be severe)</p> <p><u>In the zones C.2 and C.3</u>, increase of rains means:</p> <p><u>Pos.</u> - Higher water availability at the beginning and end of growing season</p> <ul style="list-style-type: none">- Lower air temperatures <p><u>Neg.</u> - Higher leaching of soil nutrients</p> <ul style="list-style-type: none">- Higher soil erosion- Lower photosynthesis (due to lower radiation)- Higher risks of disease- Greater difficulty in ripening and harvest processes

Table 11

Consequences of an increase of climatic variability
for traditional rainfed agriculture

1. Greater risks of unsuccessful sowings
2. More frequent and consistent soil erosion
3. Great risk of crop failure
4. Tendency towards desertification

Effects of variability of temperatures during
the dry season

Tendency towards:

Lower minima

Higher maxima

Pos. Better development and growth
of temperate crops (wheat,
barley)

Neg. For temperate crops:
Too fast ripening and maturation;
disequilibrium in water uptake

Neg. Risk of retarding the growth
of tropical crops

Neg. In general:
Increase of crop water requirements

The outcome would be a tremendous waste of energy and wealth. It is necessary that some traditional technologies be slowly replaced by more efficient ones which would enable farmers partially to overcome the disadvantages linked with inadequate criteria of soil and crop management and which could be easily accepted by farmers. As an example, the replacement of hand soil work by animals may represent a first simple step for improving soil preparation and water storage, particularly in more arid areas. This would be an easy way of partially overcoming the adverse effect of prolonged dry spells.

Plant breeding will play an essential role in tropical agriculture. Recent examples show the importance of such assumptions (see results of IRAT activity in plant breeding /20/). However, the activity of plant breeders should be based more on agroclimatological information on the area concerned.

Soil works, the wise use of fertilizers, correct soil protection may also be easy techniques which can be greatly helped by the quantitative evaluation of the occurrence of adverse weather behaviour.

In conclusion, a limited degree of technological input seems advisable for improving the resistance of traditional agrosystems to the anomalies of climate (see also Table 12). Further introduction of new technologies, however, will only be useful if the infrastructure of agricultural areas, such as technical assistance to farmers, is substantially improved.

Table 12

Criteria for land and crop management for improving
the agrosystem's resistance to climatic variability

Tendency towards:	
<u>Drier climate</u>	<u>Wetter climate</u>
Plant improvement: Selection and utilization of non-photosensitive and drought-resistant varieties	Plant improvement: Photosensitive pest-resistant varieties
Timely soil preparation: Deeper soil ploughing for increasing storage of water	Improvement of soil drainage systems (mainly in the C.2 and C.3 sub-zones) Increase of cattle rearing in the fallow soils
Take into consideration the possibility of repeated sowings (with mechanization)	Timely sowing for faster soil cover and to avoid losses of soil nutrients
Strict control of stock-carrying capacity of pasturelands and fallows	Increase the use of fertilizers mainly in the C.2 and C.3 sub-zones

4.3 The role of agrometeorology

The inadequacy of agroclimatological and agrometeorological knowledge in the tropics does not need further emphasis. Almost all climatological information for agriculture comes from the data collected in the meteorological networks set up for assistance to civil aviation.

A drastic intervention in the sense of a re-orientation of meteorological services towards agriculture seems imperative. It is not an easy task, however, since it means the presence of expert personnel, the assessment of the needs of single agricultural areas, co-ordination with other agricultural services.

Nevertheless, a greater and more agriculturally-oriented exploitation of existing meteorological data seems essential in order to make a more careful analysis of the agroclimate and its anomalies in time and space. Moreover, some simple synoptic data can be utilized for many agricultural purposes. Among them it is worthwhile underlining the importance of the early warning system carried out in recent years by FAO and WMO [21].

This consists of a continuous monitoring of the situation of the water balance of the semi-arid areas of tropical Africa during the entire growing season. Rainfall data and evapotranspiration are utilized for this purpose and appropriate coefficients will be utilized according to the soil conditions, the more common length of the growing season for the most important crops, etc. On this basis a forecast of final yield seems possible and the results of the 1978 rainy season have confirmed the value of this system.

It may be concluded that this may represent a fundamental tool in the hands of decision-makers and for the organizations which take care of the assistance to the countries affected by crop failure due to adverse weather conditions. The results to date of such a system seem very favourable and its reinforcement may be highly advisable in the fight against the effects of the variability of climate.

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CLIMATIC CHANGE AND THE EXPLOITATION OF

CLIMATIC RESOURCES IN CHINA

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1. Introduction

There are numerous climatic records in Chinese historical writings. As far back as two thousand years ago, there was a literature describing climatic anomalies which affected the harvests. The pioneer works of Chu Ko-chen, especially one recent paper [1], stimulated the study of climatic changes in China.

In 1975 and 1977, studies on rainfall conditions in the past 500 years were made by a cooperative team consisting of members from the Research Institute of the Central Meteorological Service, from provincial Meteorological Services and from the Universities of Peking and Nanking [2]. Dryness/wetness grade series have been proposed for 126 small regions. For every small region, year-by-year dryness/wetness grades have been deduced from local gazetteers. The grades are wet, sub-wet, normal, sub-dry and dry, denoted by 1, 2, 3, 4, and 5 respectively. For most of these small regions, the series begin from the year 1470, except some within bordering provinces. A set of yearly dryness/wetness distribution charts has been drawn for the period 1470-1977.

Recently, from climatic descriptions in more than a thousand volumes of prefecture and county gazetteers in our sub-tropical and tropical provinces, a study of the time series of a relative index of winter severity for every decade in the last 500 years has been undertaken [3]. Dendrochronological studies have also been carried out in several regions.

Agriculture is the basis for the development of the national economy in China. It is a major task of our meteorological services at different levels to serve agricultural production. Research into climatic changes and better exploitation

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of climatic resources are an important facet of rendering good service to agricultural production.

It is the purpose of this paper to present briefly the results of some recent studies on climatic change in China, with some remarks on the problem of exploitation of climatic resources.

2. Main features of temperature changes

In Figure 1, temperature changes for various time scales are outlined, the changes for the last 5 000 years being more or less detailed. In 1 an attempt has been made to prove that during the archaeological period c. 3000-1100 B.C. (from Yang-shao culture to Yin-hsu culture), based on materials obtained from historical writings and excavations, the average annual temperature for most of the time was about 2 deg C higher than that of the present, with January temperature 3-5 deg C higher than it is today. Because of the limitations of the data, it is not possible to study the fluctuations in this period. After this period there was a series of fluctuations of amplitude about 1-2 deg C, at approximately 1000 B.C., 400 A.D., 1200 A.D. and 1700 A.D. In the Han (206 B.C. - 220 A.D.) and the Tang (618 - 907 A.D.) dynasties, the climate was comparatively warm. Within each period of 400-800 years, smaller cycles of 50-100 years can be discerned, with amplitude of 0.5 - 1 deg C. In these cycles the coldest periods seemed to begin at the coast of Europe and Africa. There was also a tendency to propagate from the north to south.

From Chang and Chu's study 3 of severe winter temperatures in the last 500 years, some differences are found among the five tropical and sub-tropical climate regions studied (Figure 2), but three major fluctuations can also be discerned. Periodicity analysis shows a marked period of about 170 years. For instance, in the lower reaches of the Yangtze River, cold periods occurred in a period ending in 1510, in 1621-1690 and in 1812-1880, and warm periods in 1511-1620, in 1691-1810 and in 1881-1940.

By appropriate statistical analysis, the climatic descriptions in historical writings of Shanghai are converted into 10-year means of winter temperature (Figure 3). It shows that the variation of ten-year winter temperature is somewhat higher than 2 deg C. In the recent 20-30 years, neither very severe nor very warm winter temperatures have exceeded the estimated range of variation for the past 500 years.

Power spectrum analysis of monthly and annual temperatures in our instrumental observation period shows biennial oscillations, especially in winter and spring months. In addition, there may exist 22-year and other cycles for winter months.

Winter temperatures in China are closely related to circulation conditions 4. In cold periods, the Mongolian high pressure on the mean sea-level pressure charts intensifies and becomes predominant. On the mean 500 mb charts, the ridge east of the Ural Mountains becomes a pronounced feature and the East Asiatic trough near 140°E intensifies. These cold periods occur mostly in the transitional stage from the minima to the maxima in the zonal index cycle. The situations are reversed for the warm periods.

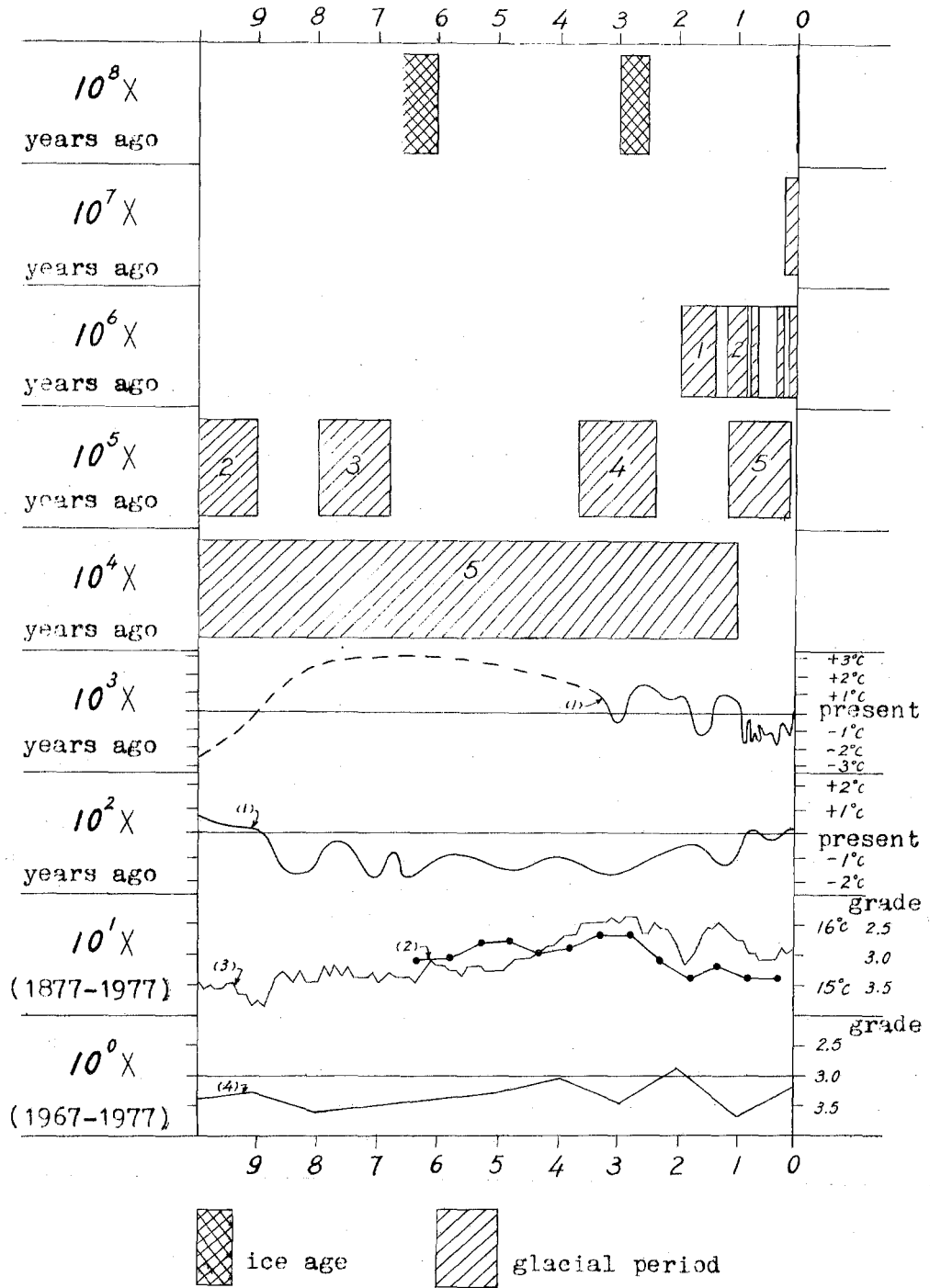


Figure 1.

General trends in temperature of various time scales in China

- (1) based on ref. 1
- (2) 5-year mean grades of temperature
- (3) 5-year running means of temperature for Shanghai
- (4) temperature grades

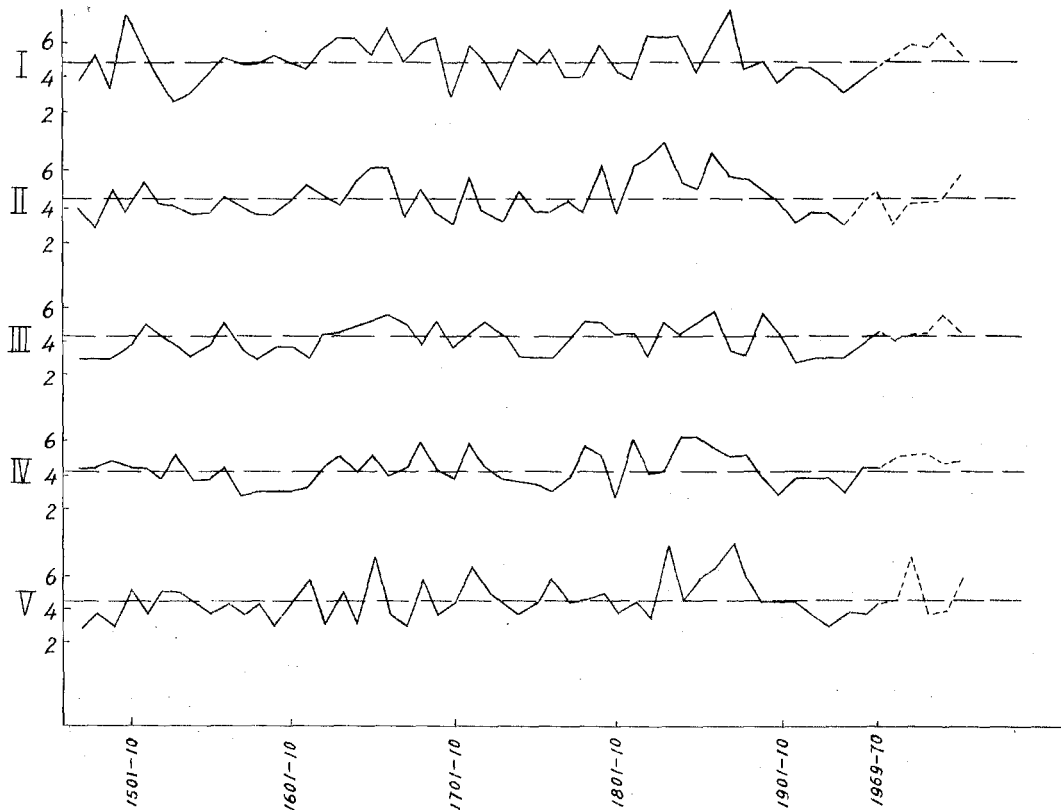


Figure 2. Winter temperature index of five regions.

- I. Lower Yangtze Valley
- II. Middle Yangtze Valley
- III. Hunan and Kianghsi Provinces
- IV. Fukian and Chekiang Provinces
- V. Kwangtung and Kwanghsi Provinces

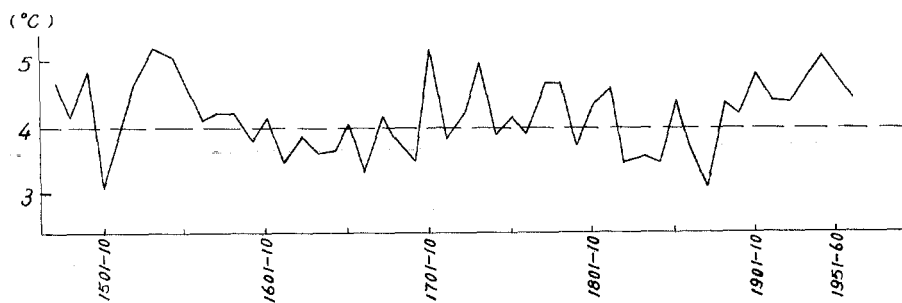


Figure 3. 10-year mean winter temperature (°C) of Shanghai

3. Main features of the dryness/wetness distribution in the past 500 years

Five types of distribution of dry/wet areas have been found by means of empirical orthogonal function analysis and other statistical methods 5,6. The basic feature and typical year for the five types are as follows:

- I Wet along Yangtze basins. (1911)
- II Wet south of Yangtze, dry north of it. (1586)
- III Dry along Yangtze, with two wet belts, north and south of Yangtze. (1652)
- IV Wet north of Yangtze, dry south of it. (1895)
- V Dry most of the country, except in western parts. (1528)

Table 1 shows the occurrences of each type for 50-year periods. It can be seen that Type I prevailed in periods 1551-1600 and 1751-1800. Occurrence of Type II increased in periods 1601-1650 and 1801-1900, then Types III and IV in 1651-1700 and 1851-1900. The preponderance of the Types I-IV appeared in succession and this suggests a wetness cycle of about 200 years, a result that has been supported by other studies. For the recent centuries, the 14th century and the latter half of the 16th century were very wet, while the 17th century was very dry. The latter half of the 18th and the 19th century turned to be wet again and the first half of the 20th century became dry. In the earlier centuries, 10-11th, 8th, 5th and 2nd-3rd were rather wet, while the 12th, 9th, 6-7th and 4th century were dry, suggesting a cycle of about 200 years as well.

Table 1
Occurrences of types of wetness patterns

Period	Type I	Type II	Type III	Type IV	Type V
1470-1500	10	14	4	1	2
1501-1550	13	10	12	6	9
1551-1600	<u>22</u>	12	7	6	2
1601-1650	10	<u>17</u>	7	9	7
1651-1700	18	4	<u>13</u>	<u>12</u>	3
1701-1750	18	10	<u>9</u>	9	4
1751-1800	<u>19</u>	9	10	9	3
1801-1850	16	<u>12</u>	8	9	5
1851-1900	9	13	<u>13</u>	<u>12</u>	3
1901-1950	12	11	11	6	<u>10</u>
1951-1977	4	5	5	6	<u>7</u>
average	14.8	11.6	9.8	8.3	5.5

A comparative study of the rainfall observations in Shanghai for 1873-1972 with the wetness/dryness grades has been carried out. Grades 1-5 correspond to annual rainfall of 1 485, 1 285, 1 135, 1 010 and 860 mm respectively. The grades in the decade 1561-1570 were: six years with grade 1, four years with grade 3. The decadal mean corresponds to about 1 350 mm rainfall, while the maximum rainfall of any ten-year period during the last 100 years was only 1 260 mm. In the dry decade 1635-1644, there were four years with grade 5, 4 years with grade 4 and two years with grade 3; the corresponding decade mean rainfall was 975 mm, which is a low value that has never occurred in the past 100 years. This suggests that the observed rainfall variation in the past 100 years may be much smaller than that in the earlier centuries.

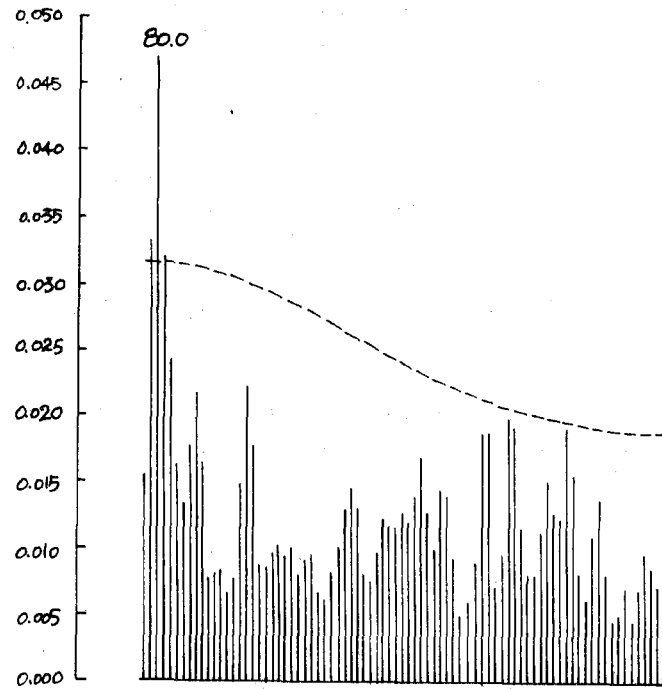
The cycle of about 80 years is marked in north China and lower Yangtze as shown in the spectrum analysis of the wetness/dryness grade series (Figure 4). This has also been supported by other studies.

The shorter cycles are mainly of 36-year, 22-year and 2-3 year duration. Power spectra (N=100, M=55) for six representative locations are given in Figure 5, Figure 5a, the curve for Hsinyang (Honan province), shows a main cycle about 100-year; in Figure 5b, the curve for Shanghai, quasi-biennial and 36-year cycles are marked. Figure 5c, the curve for Talién (Liaoning) shows mainly the 22-year and 2-year cycles. Figure 5d shows an 11-year cycle for Anyang (Honan). In Figure 5e for Nanchang (Kiangsi), the 6-year and 2-year cycles are marked. The quasi-biennial cycles dominate in Sanming (Fukien), as shown in Figure 5f. The regions in which the various cycles dominate are shown in Table 2.

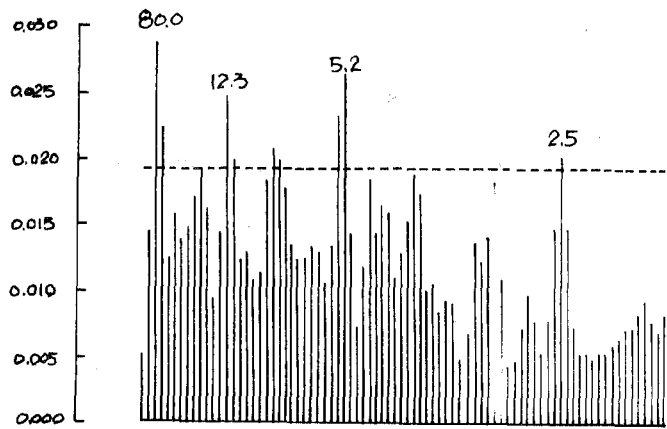
Table 2

Main cycles of dryness/wetness and their dominant regions

Cycle (yrs)	36	22
Regions	Lower Yangtze, N. China plains, Kwangsi, Hainan.	NE regions, Paohai Gulf, middle Yangtze
Cycle (yrs)	11	5-6
Regions	Yellow River drainage, Hsi-Kiang drainage Taiwan	Basins south of Yangtze, Yunnan Kwangtung
Cycle (yrs)	quasi-beinnial	
Regions	Yangtze Basins, Basins south of Yangtze	



a



b

0 10 20 30 40 50 60 70 80

Figure 4. Dryness/wetness power spectra (N=508, M=80): (a) Peking, (b) Nanking

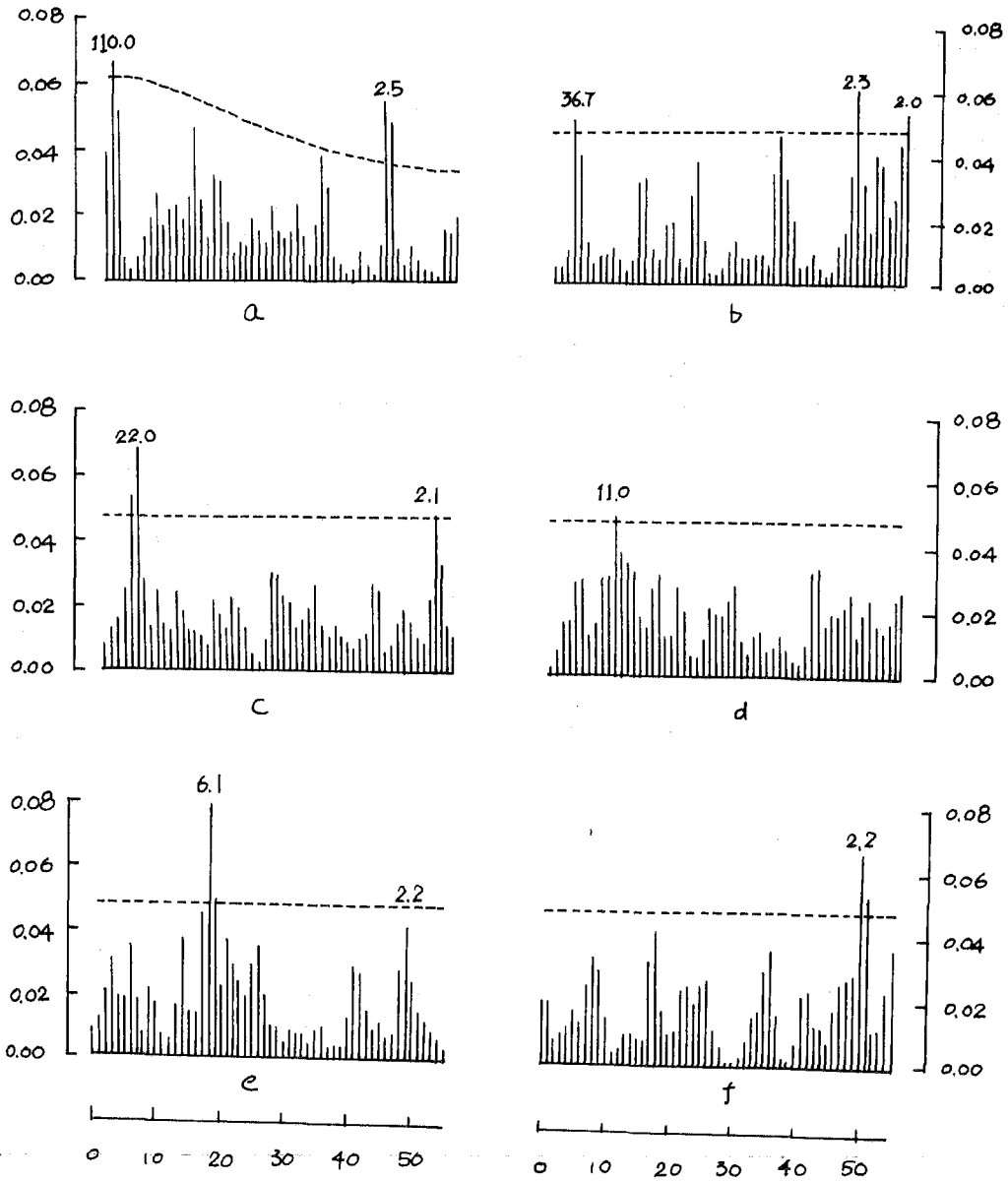


Figure 5. Dryness/wetness power spectra:
(a) Hsinyang (b) Shanghai (c) Talien
(d) Anyang (e) Nanchang (f) Sanming

In the cycles mentioned above, the 36-year and 22-year cycles have been discussed by many authors. More attention has been paid to the important quasi-biennial cycles of rainfall. The 36-year and quasi-biennial cycles appear to be important components in wetness variation in China.

It has been found that circulation conditions are different for variations with different frequency. Figure 6 shows correlation between the dryness/wetness grades for Shanghai and global sea-level pressure in July, for low frequency (a) and high frequency (b) variations. In differentiating variations of low and high frequency, both the pressure series for each location and the dryness/wetness grade series are smoothed by taking weighted 3-year running means, with weighting factors 0.23, 0.54 and 0.23, in order to filter out the 2-3 year cycles and to obtain a series in which the low frequency variations become dominant. Subtracting the low frequency series from the original series, the series in which the 2-3 year cycles dominate are obtained. These two kinds of series are used to calculate the correlations and it is found that, for low frequency variations, maximum correlations lie in the middle equatorial Pacific and Australia; for high frequency variations, in east Asia.

In the same work, taking pressure difference between locations 10°N, 160°W and 20°S, 140°E as the Southern Oscillation Index (SOI) (see overview paper by Hare) and the sum of pressures at locations 50°N, 130°E and 50°N, 140°E as East Asia Circulation Index (EAI), their correlations to dryness/wetness grade series are calculated. In Table 3, the number of locations out of the 100 locations in East Asia, showing correlations to SOI and EAI with confidence limit reaching 95 per cent are given. Table 3 shows that, for both indices, correlations for low and high frequency series exceed that calculated from the original series. EAI is well correlated to high frequency variations of dryness/wetness, while SOI has pronounced correlations to low frequency ones.

Table 3

The number of locations with confidence limit 95 per cent for correlations between circulation indices and dry/wet grades.

Index	EAI			SOI			
	Orig.	LF	HF	Orig.	LF	HF	
Corr.	-	13	16	19	7	31	9
	+	3	1	10	0	1	3
Total	16	17	29	7	32	12	

Figure 6a shows the distribution of correlations between EAI and the high frequency dryness/wetness grades in China. High EAI accompanies wetness in the Yangtze basins (negative correlation) and dryness in south China, the northern part of north China and the north-east region. The situation is reversed when EAI is low. The distribution of correlations between SOI and the low frequency dryness/wetness grades is given in Figure 6b. Most parts of China are wet when SOI is high, especially in the Yangtze basins, south China, the southern part of the north-east region and the northern part of north China.

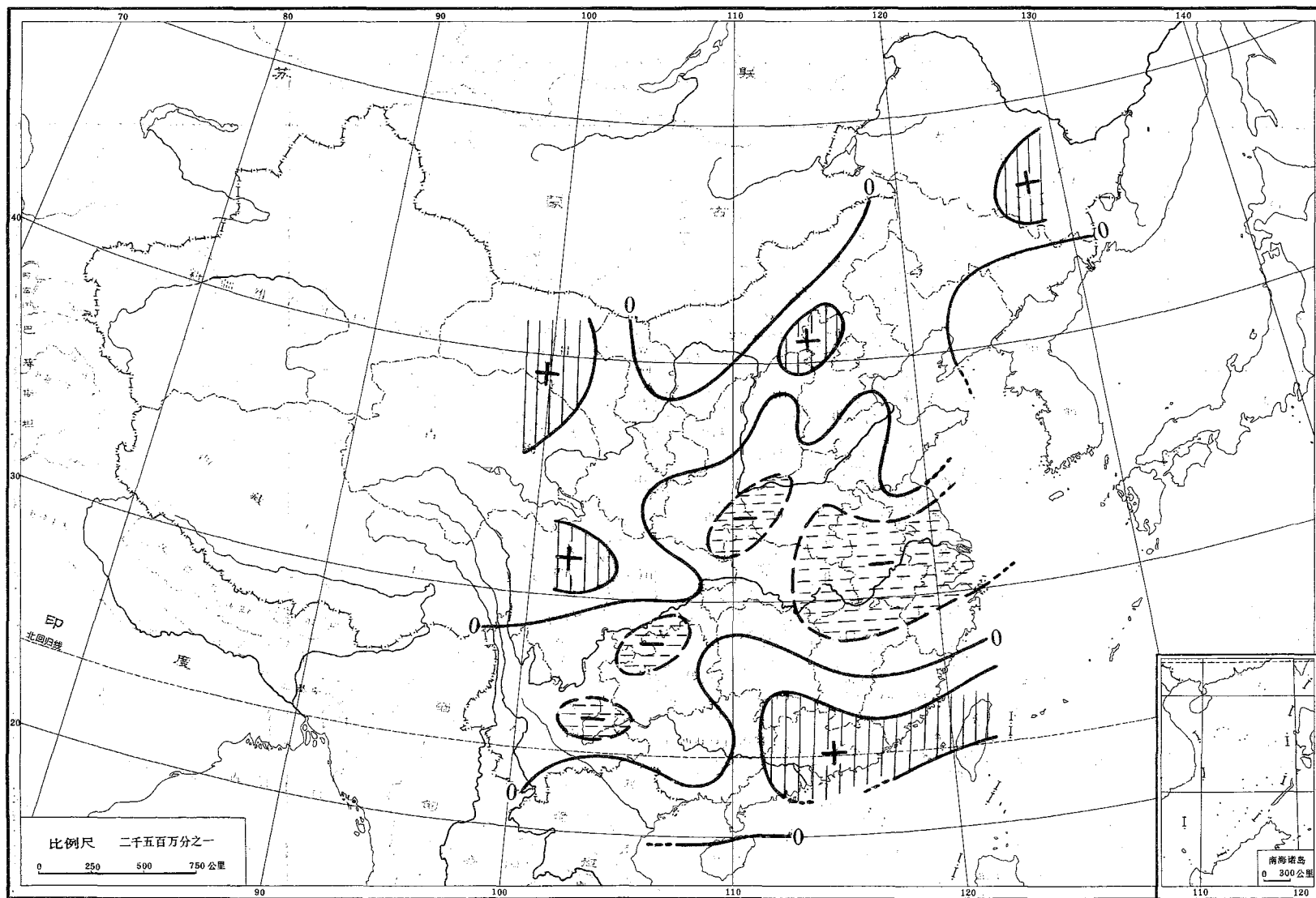


Figure 6a Distribution of correlation between EAI index and the high frequency dryness/wetness fluctuations

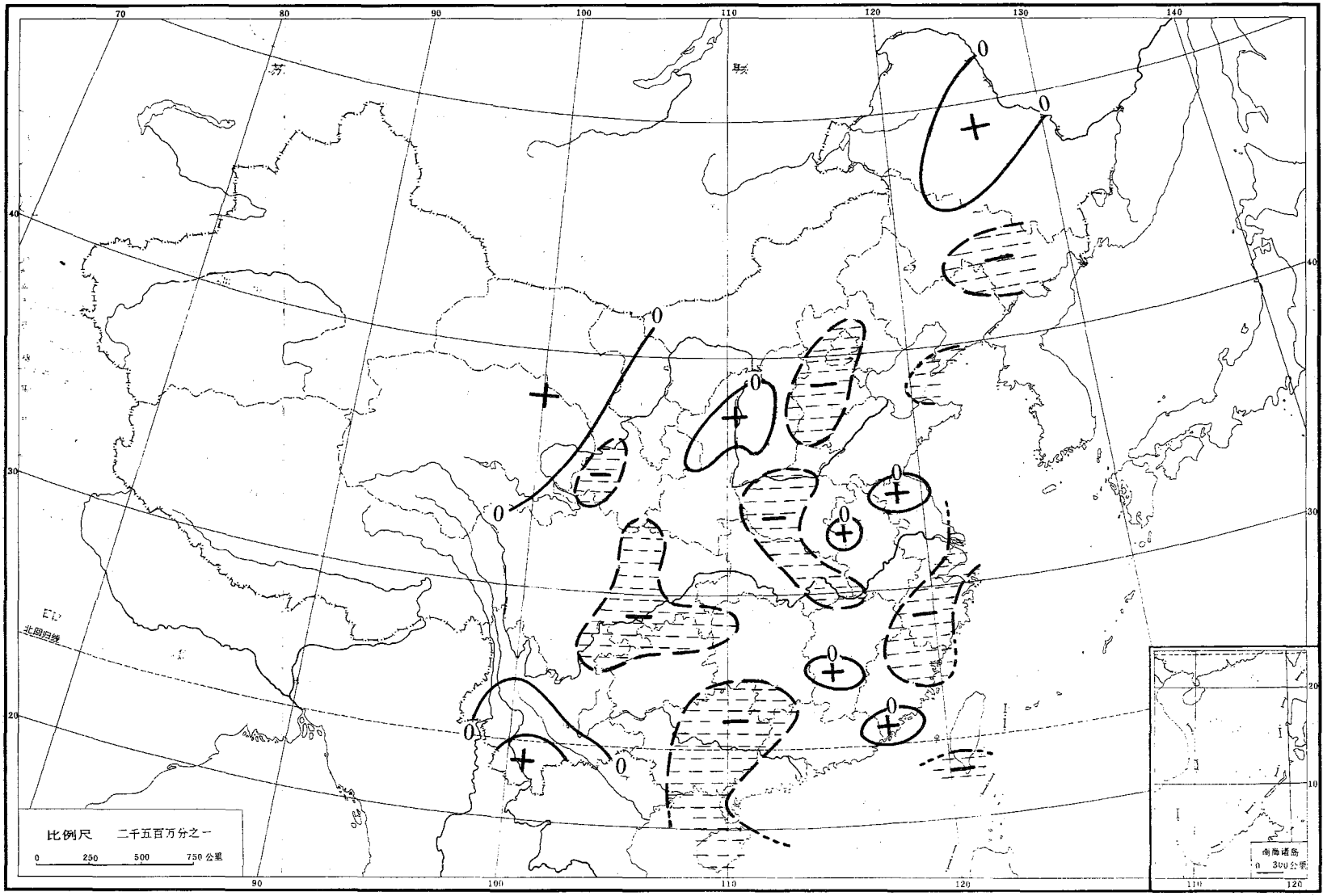


Figure 6b Distribution of correlation between SOI index and the low frequency dryness/wetness fluctuations

To sum up, climatic variation in China is characterized by cold/warm and dry/wet quasi-periodic alternations on various scales. There is certain association between the cold/warm and dry/wet cycles. For example, in the 11th century, China was undergoing a process of temperature decrease while at the same time wet periods were of longer duration. Table 4 shows the alternations during the period of instrumental observation.

Table 4

Relationship between dry/wet and cold/warm features period

Period	1901-1910	1911-1920	1921-1930	1931-1940
	dry	wet	dry	wet
	warm	cold	warm	cold
Period	1941-1950	1951-1960	1961-1970	
	dry	wet	dry	
	warm	cold	cold	

4. On the exploitation of climatic resources

Climatic change and variation have much to do with the exploitation of climatic resources. China is rich in climatic resources. The potential of light utilization is very high [7]. In many arid regions, with abundant sunshine and adequate temperatures some oases have recorded good yields of spring wheat, as high as 12.7 tonne/ha [8]. Nevertheless, in southern parts of China, sunshine may be very deficient in certain months. For instance, in March 1970, the sunshine hours in the Szechuan basin were less than 50 per cent of the normal amount, in some parts even less than 20 per cent.

Water utilization estimates based solely on local rainfall and evapotranspiration show a fairly high level in many regions. When regional water use is considered, the potential of diverting water from outside and tapping ground water is high. Hence water conservancy is considered as the lifeline of agriculture.

Climatic limitations to agriculture production potential may be conceived as composed of two parts. The part determined by the present mean climatic

conditions and their associated deviations may be called regular limitation. The other part, controlled by the trend of climatic change may be called irregular limitation. Of course, their effects are interrelated.

Experimentation and adoption of optimum cropping systems based on local climate, crop conditions and economic conditions may reduce the regular limitation. For example, in 1972, Peking suburbs succeeded in triple-cropping in plains in order to replace the single cropping or three-cropping-in-two-years systems, by making good use of interplanting and undersowing: interplanting wheat with corns and then replacing wheat with millets, kaoliang (sorghum) or clover. The total yield reached 6-8 tonnes/ha 9. This system makes the growth season of corn about one month longer and increases effective accumulated temperature by 700-800 degrees. The light requirements are high in the middle portion of growth periods for all three crops. The new system by careful timing makes the best use of sunshine and the use of water is also more efficient.

Tachai production Brigade, an outstanding unit in China's agriculture, has turned barren hills into terraced fields, transforming their leaking fields to conserve water and the applied fertilizers and to prevent erosion. The Brigade also constructed a spongy field of foot-thick fertile soil suitable for resisting droughts. In 1972, a year of severe drought, measurements made in July showed that moisture content in the spongy field exceeded that of the ordinary fields by an amount equivalent to 3-5 mm of rainfall. Many kinds of such capital farmland constructions may serve as effective measures of reducing the regular limitation to exploitation of climatic resources.

The better the climatic resource is exploited, the greater the sensitivity to climatic variations. Historical writings reveal that double rice-cropping systems had been adopted in lower Yangtze in the fifth, eighth and eighteenth century. An officer in Soochow experimented double-rice cropping as well as regenerated rice in 1715-1720 and obtained average yield of 6.2 tonnes/ha (maximum 7.6 tonnes/ha in 1718). The practice had been extended to neighbouring counties. But it failed in the early 19th century due to the climate turning cold 10. This historical passage vividly testifies the relation between climatic change and cropping system. We are now engaged in improving our cropping systems to strive after higher yield and therefore knowledge of the prospect of climatic fluctuation is very necessary. Of course, owing to rapid development of agro-science and economy, our cropping systems would not hinge entirely on climate.

Agricultural production is conducted in relatively warm seasons, so we must take into account the duration of growing period and the accumulated temperatures, which are influenced by the climatic trend. The variability of temperature in China is prominent. For instance, during 1876-1895, there were 11 years in Shanghai with annual mean below 15.1°C and no years above 15.8°C; while during 1936-1955, 12 years above 15.8°C and no year below 15.1°C.

The effects of shorter quasi-periodic oscillations of rainfall could be regulated by large reservoir systems to save surplus water in wet periods for use in dry periods, and to reduce flood or drought disasters. A large engineering project

of diverting the abundant water in the lower reaches of the Yangtze River to north China is being planned. There are many regions in China engaging in afforestation, construction of terraced fields, dykes and dams, and detention of run-off to recharge underground water, for the purpose of counteracting rainfall irregularity. The planned development of agriculture, forestry and animal husbandry should lead to the establishment of an optimum agricultural ecosystem, which in turn may alleviate the impact of extreme conditions in fluctuations.

Now, in order to effect an upswing in agriculture, our country relies mainly on forging ahead with farmland capital construction, stressing soil improvement and water control, practicing scientific farming, and speeding up mechanization. How to upgrade our capability of predicting and coping with natural calamities is a scientific problem of great importance to agricultural development. The study of climatic change is one facet of this effort.

If reliable prediction of climatic change can be made, it should be possible to adapt the cropping systems to the changing conditions to ensure high and stable yield. Recently, climatic forecasting has already been experimented with in several meteorological services and research institutes. In 1972, a year of severe drought, a good forecast was made for Shanghai of the trend towards rainfall increase by analysing the 36-year and 2 to 5-year cycles and the solar activity. Kilin meteorological service, in the northeastern part of China, susceptible to low summer temperatures, predicted in 1962 that, beginning 1962 or 1963, there would begin a dry period persisting for about eleven years, which has been fairly well verified.

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RENEWABLE RESOURCES AND AGRICULTURE IN LATIN AMERICA

IN RELATION TO THE STABILITY OF CLIMATE

Juan J. Burgos*

1. Climate as an economic resource

The idea of climate as an economic resource is a relatively new one. Schemes which man has devised in relation to economic resources in order to satisfy his needs have tended to ignore the question of climate. In the first place it is difficult to formulate an integrated conception of what climate actually is; secondly, climatic conditions have only been appreciated at times of disastrous events such as droughts, floods and frosts.

The continental droughts of the 1930s, which affected both hemispheres, produced dustbowls in the central states of the USA and a similar phenomenon in the western region of the Argentine pampas; many people regarded these phenomena as largely irreversible. Events such as these awakened national and international awareness to the need to regulate the use and management of renewable natural resources. Conservationist movements were opposed to the indiscriminate consumption of natural resources in pursuit of economic growth. Such resources include water, soil, vegetation and animal life, which are renewable resources, and coal, oil and other mineral products which may be described as perishable resources.

In recent years climatological information has been applied over a wide range of practical problems and as a result there has been growing recognition of climate as an economic resource. Davitaia 1, 2 and other Russian writers have used the concept of agroclimatic resources and climatic resources in order to define the climatic conditions that are of economic significance. Maunder 3, Taylor 4 and Perry 5 used concepts like "econoclimate" models based on climatic parameters according to their economic importance but considering climate in a stationary state.

It is necessary to appreciate that climate is not a stable resource. Occurrences such as droughts in different parts of the world and other dynamic events have given evidence of the variability of climate and of the possibility of long term changes. In addition, there has been much concern over the last decade that the activities of

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man may change the climate, perhaps irreversibly. Increased concentrations of carbon dioxide and aerosol gases in the atmosphere, the spread of deserts and deforestation are seen as consequences of human activity which are capable of causing changes in such important climatic factors as the global circulations of the atmosphere and the oceans and also in the polar ice-caps. It is suggested, therefore, that economic planning must take into account the potential for climatic change and climatic variability due to human activities. Figure 1 from a paper by Burgos [6], illustrates a simple dynamic system between climate and resources of economic value, divided according to their characteristics and stability, as follows:

- (a) natural resources, i.e., those provided by nature and used by man as they are - depending upon their stability they may be:
 - (i) stable - solar energy and tidal energy
 - (ii) quasi-stable- climate, atmospheric gases
 - (iii) renewable - water and soil, natural vegetation and animal life
 - (iv) perishable - mineral output and fossil energy;
- (b) artificial resources, i.e., those produced by man through changes in natural resources and those produced by his own activity. Depending upon how stable they are, they may be divided into:
 - (i) renewable resources : forestry production, agricultural production and animal production
 - (ii) non-renewable resources : industrial output and commercial and financial production.

The evaluation of a system such as the one proposed would be of interest not only in relation to prediction of future changes in the climate but also to a better analysis of our present climate. Such an examination would be carried out through an analysis of the intensity and nature of any changes in the climate. Moreover, a quantified system would be of use in rational programmes for economic growth which would endeavour to avoid unfavourable changes in mankind's environment.

2. Potential productivity of the soil in Latin America

2.1 Productivity in earlier centuries

Latin America is formed by Ibero-American countries occupying the South American sub-continent, Central America, the southern portion of North America and the larger Caribbean islands, between 32°N and 55°S approximately. Those small parts of South America and the Caribbean whose culture is not Iberian in nature are not very different physically or ethnically from the rest of Latin America. The specific physical facts concerning this geographical area are:

- (a) the large area of land with tropical, sub-tropical, humid and sub-humid climates;

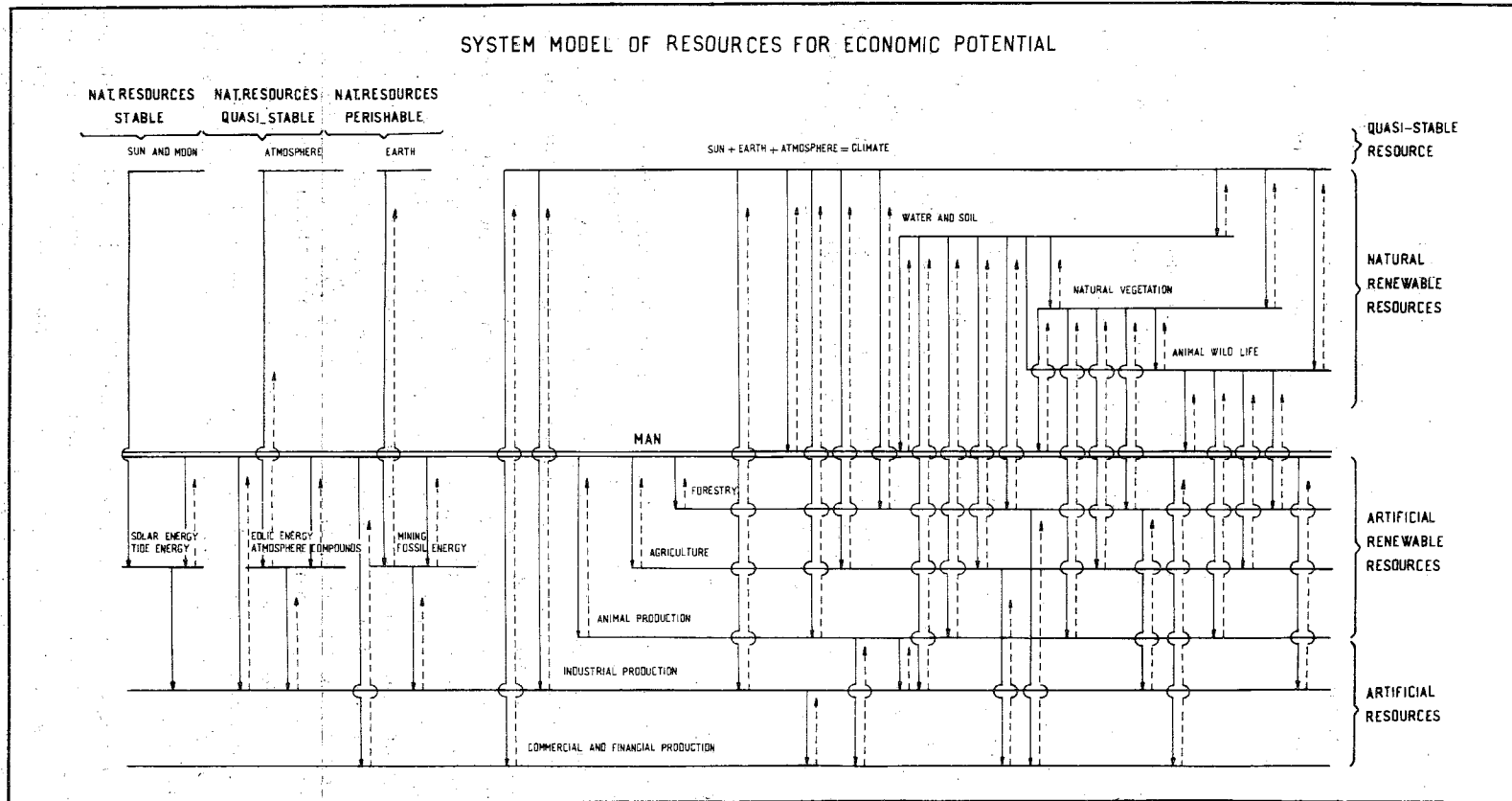


Figure 1. System Model of Resources for Economic Potential. Source: 6.

- (b) areas with high altitude climates, particularly along the Andes mountain range; and
- (c) the arid and semi-arid tropical and sub-tropical climates.

The temperate and cool climates are to be found in relatively limited areas, at extreme latitudes or in the mountain peaks. Further in the latter, one can only make out a reduced variety of sub-types, by reason of the predominately oceanic macro-climate to which the area is subject.

The renewable natural resources of the Latin-American sub-continent were for a long time in dynamic interchange with the physical environment. Man only impinged upon the natural resources to satisfy his needs and he was not a threat to the stability and renewal of those resources. The aborigin populations were grouped in the high territory, within the limits of the dry or semi-dry climate, and agriculture was only used for local subsistence.

Agriculture during colonial times and the first period of the independence of Latin American countries was not so important an activity that the artificial renewable resources were placed in competition with natural resources. New agricultural developments undertaken in this period were started in regions where the ecosystems were more stable such as in the sub-humid and temperate regions; similarly developments were initiated in the very arid areas where irrigation was available. The sub-humid savanna areas were left open to incipient cattle raising which was conducted on a more or less nomadic footing.

2.2 Productivity in the present century

From the beginning of this century, industrial development, including mechanization, the construction of irrigation works and the use of fertilizers and pesticides, contributed to a massive growth in agricultural activity. Furthermore, since the countries which were affected were under-developed and since the new technology gave readier access to renewable natural resources, agriculture was given the highest priority in programmes for economic growth. With the passage of years, however, renewable artificial resources - and indeed man himself - have become directly competitive with natural resources. Already many delicate ecosystems have been destroyed and there is a serious threat to other ecosystems, as yet untouched, because of the possibilities for population expansion in the sub-continent. Table 1 shows the growth of population in 20 Latin American countries 7. It is to be expected that countries in the first column will at least double their populations in the next 20 years and that in the remainder the population increase may be of the order of 50 per cent. Over the next two decades, therefore, the output of renewable artificial resources should be doubled if internal needs are to be met and a satisfactory export surplus maintained.

It is worthwhile to assess the potential suitability of the climate in the area for the renewable artificial resources which tend anyway to encroach aggressively upon natural resources. In very general terms the renewable artificial resources may be divided into forest production, agricultural production and animal production.

Order	Country	Actual Population 1 000 hab.	Population Growth per cent	Order	Country	Actual Population 1 000 hab.	Population Growth per cent
1	Ecuador	7 555	4.02	11	Costa Rica	2 065	3.17
2	El Salvador	4 375	4.00	12	Surinam	447	2.88
3	Dominican Rep.	5 471	3.97	13	Bolivia	4 761	2.84
4	Mexico	63 266	3.96	14	Guyana	827	2.55
5	Colombia	25 226	3.95	15	Cuba	9 889	2.23
6	Venezuela	12 947	3.51	16	Chile	10 633	2.07
7	Peru	16 242	3.49	17	Haiti	4 703	1.66
8	Brazil	116 139	3.39	18	Argentina	26 056	1.45
9	Panama	1 774	3.39	19	Trinidad	1 030	1.12
10	Paraguay	2 805	3.26	20	Uruguay	2 855	1.09

Table 1

Actual Population and index for population growth calculated from data of the period 1965-1977 in 20 Latin American countries in order of growth index

Source: 6

2.3 Climatic suitability for forestry

In Figure 2 we show the suitability of the South American climate for forestal production on the basis of straightforward agroclimatic parameters [8]. If these parameters were applied to Central America, Mexico and the Caribbean islands similar results would be obtained. Only in the highest levels of the Andes is there an energy balance below $30 \text{ kcal cm}^{-2} \text{ year}^{-1}$, equivalent to less than 500mm of potential evapotranspiration each year which is sufficient only for the formation of tundra. In the rest of the continent tree growth will only be limited by a shortage of water.

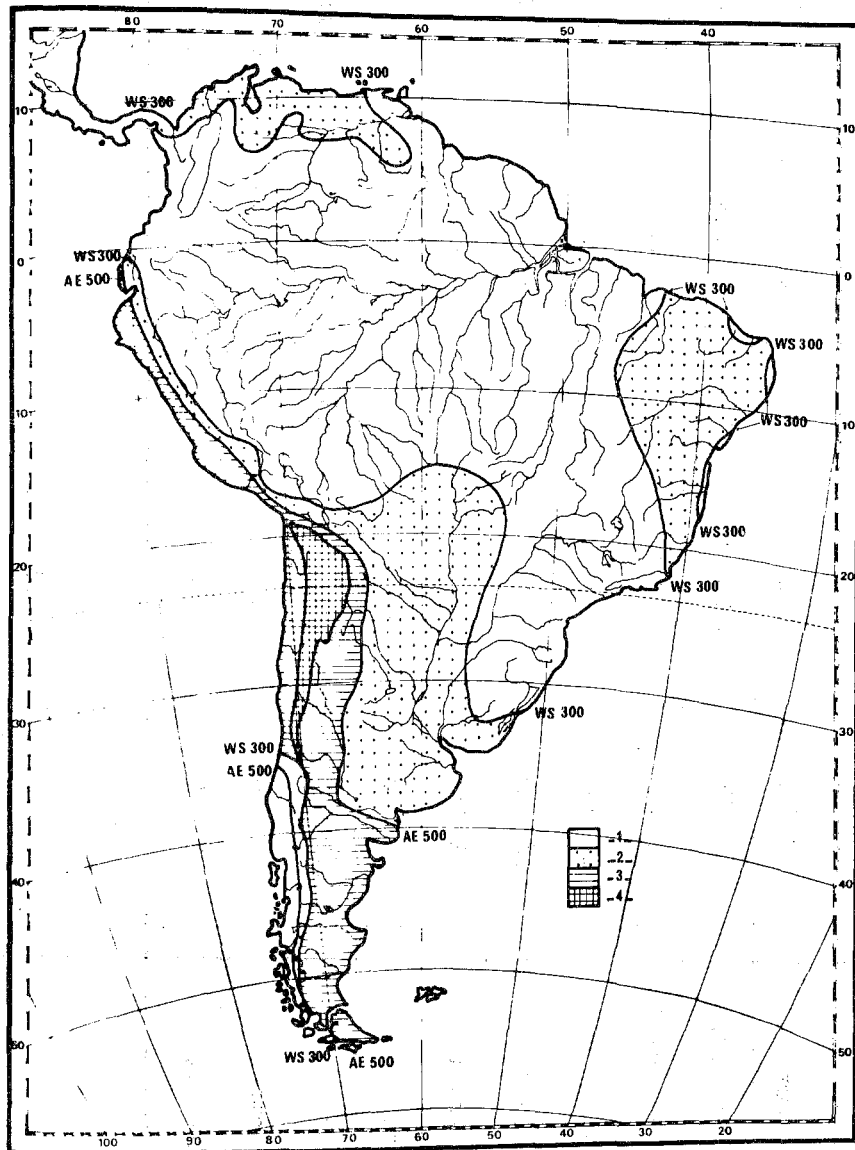


Figure 2. Forest and foresting regions in South America. (1) Hygrophytic forest and foresting areas without irrigation. (2) Xerophytic forest or hygrophytic foresting areas with irrigation. (3) Xerophytic and hygrophytic foresting areas with irrigation. (4) No foresting areas. WS, annual water surplus. AE, annual actual evapotranspiration. Source: [8].

The dampest areas of the continent are in the north where the rivers Cauca, Amazon, Magdalena, Tocantins and a part of the Orinoco have their basins. The conditions are the same as those of the area where the San Francisco, Parana and Uruguay rivers have their high basins. There are also damp areas in the central southern area of Chile and the southwest of Argentina. These areas have a positive annual water balance with excesses of more than 300 mm and may be considered suitable for afforestation and reforestation without any need for irrigation. The natural vegetation is rain-forest and humid forest. Northeast Brazil, southern and western Uruguay, eastern Paraguay, south western Brazil, northern and central Argentina and a strip running from Bolivia through central Peru and Ecuador, together with northern Venezuela are all areas where afforestation will require irrigation, at least during the period of implantation. In these areas the actual evapotranspiration is more than 500 mm annually but the water surplus is between 300 mm and zero. In Patagonia and western Argentina, central Bolivia and a narrow coastal strip from central northern Chile to Ecuador, irrigation is absolutely vital for any form of forest growth. In these areas rainfall is so low that true evapotranspiration does not reach 500 mm; this means that not even xerophyte arboreal forms can flourish without irrigation.

2.4 Climatic suitability for agriculture

Figure 3 shows the suitability of the continent for various macro-agro-systems 8. It will thus be seen that in Patagonia, Argentina, southern Chile and the higher reaches of the Andes, valleys and plateaux agriculture will not find a favourable environment. In such areas a small amount of subsistence agriculture is possible since the average period without frosts is below 150 days.

The area which has a climate suitable for developmental agriculture (average frost free period greater than 150 days), may be sub-divided on the one hand into an area where irrigation is indispensable (where the average annual water deficit is above 200 mm or where there are more than seven consecutive months without a water deficit) and on the other hand into an area where irrigation is not necessary or will only be required occasionally to supplement local rainfall.

Insofar as the requirements and ranges of temperature are concerned, the agrosystems may be divided as follows:

- (a) tropical agriculture with no tolerance of the cold - absolute minimum temperature 6 deg C or below on one occasion in 5 years;
- (b) tropical agriculture with tolerance of cold, absolute minimum temperature -1.5 deg C or lower on one occasion in 5 years;
- (c) sub-tropical agriculture with winter ripening - absolute minimum temperature -5 deg C or below on one occasion in 5 years;
- (d) sub-tropical agriculture with summer ripening - absolute minimum temperature -12 deg C or below on one occasion in 5 years;
- (e) temperate climate agriculture - average temperature of the coldest month less than 12 deg C;
- (f) cold climate agriculture - where the annual frost-free period is shorter than 150 days.

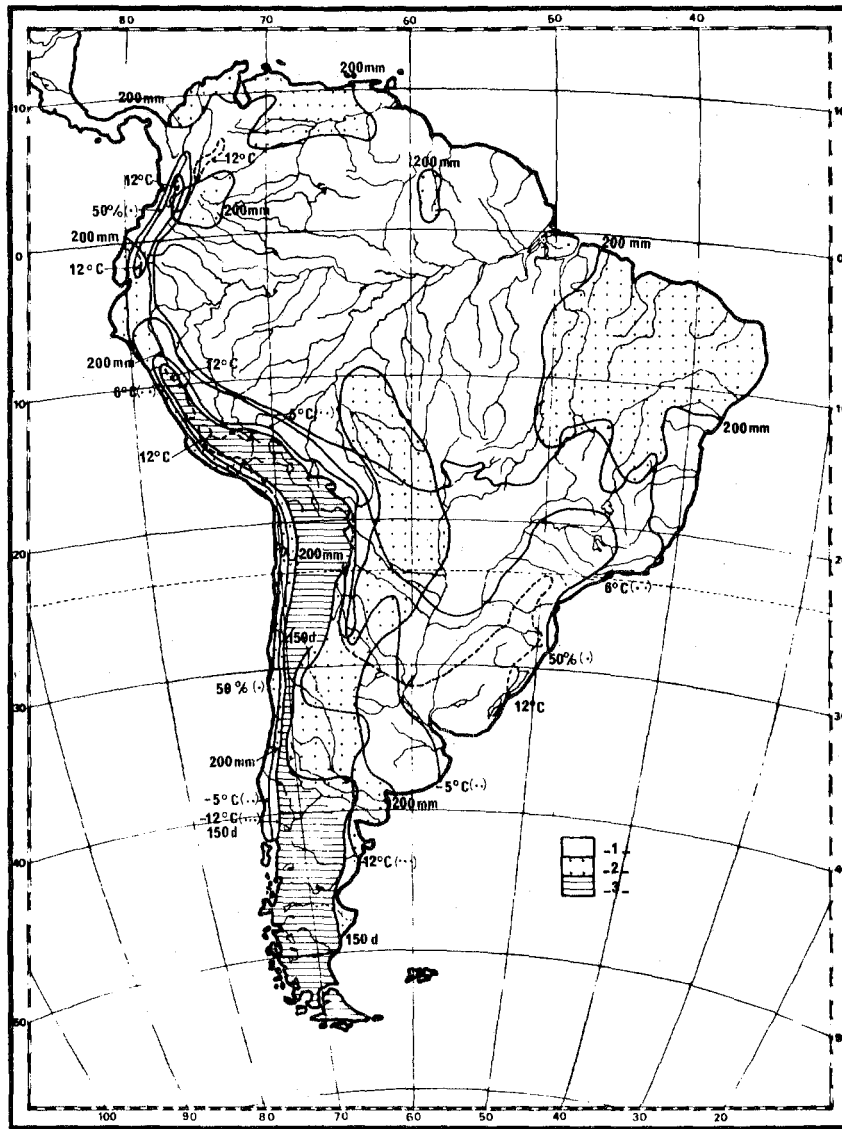


Figure 3. Agricultural regions in South America. (1) Agriculture without or with supplemental irrigation. (2) Agriculture with irrigation. (3) No agriculture areas. mm, mean annual water deficiency; d, growing season days; (.), 50% of years with annual minimum temperature ≤ 0 deg C; (..), annual minimum temperature once in every 5 years (P=20%); (...), annual minimum temperature once in every 20 years (P=5%); broken isoline, mean temperature of the coldest month. Source: [8].

It will thus be noticed that the macro-agrosystems based on irrigation within the general terms of South American capacity for developmental agriculture, are located in north-east Brazil, in a central strip of the sub-continent, to the

east of the Andes between 10 degrees and 43 degrees south through Ecuador, Peru and Chile, in a coastal strip between 0 degrees and 35 degrees south, to the west of the Andes, and in the north of Colombia and northern and central Venezuela. So far as concerns the temperature of the macro-agrosystems referred to, it will be noted that there is a large area of the continent that is suitable for tropical and sub-tropical agriculture; and that there is substantially less land with a temperate climate agriculture. The Latin-American land to the north of South America has an agricultural-suitability profile which is not essentially different and which may be analysed using the same parameters.

2.5 Climatic suitability for animal rearing

Criteria of suitability for animal rearing in Latin America are concerned with the factors that are favourable to natural pastures. It is of course possible to subject the pastures to substantial changes in order to increase output but mismanagement could degrade the pastures to near desert forms.

Figure 4 shows the sub-humid areas (dotted line) which fall within +25 and -15 on Thornthwaite's indices 9,10. The area between 0 and +25 corresponds to the normal pastures such as those on the humid Pampas in Argentina and Uruguay, the "campines" in the South of Brazil, Paraguay and Bolivia, the sub-humid - humid Llanos in the Orinoco, the peripheral Savannas of the dry north-eastern Brazil, and the humid Andean prairies in Peru, Ecuador and Colombia. The area between 0 and -15, which is drier than the previously mentioned lands, included the dry Pampas in the Argentine, the dry sub-humid "Chaco" in the Argentine and Paraguay, the sub-humid "Cerrado" in the northeast of Brazil, the dry sub-humid Llanos on the Orinoco, in Colombia and Venezuela, the interandean valleys in Bolivia, the great Guyanan savanna and the continent's sub-antarctic steppes.

Figure 4 also shows the large areas with semi-arid and arid climates that are widely used for the rearing of animals. Amongst the former and limited to the indices -15 and -40 stretch the dry Carib forests of Colombia and Venezuela, and "Cerrados" of Brazil, the dry "Chaco" of the Argentine, Paraguay and Bolivia, and the semi-arid Argentine Patagonia. The driest areas, with indices below -40, include the shrub desert in Patagonia, paramo in the high-altitude Andean plateaux, the driest Brazilian area, the "Caatinga", and the coastal deserts of Peru and Chile.

The humid regions, with indices between +25 and +40, although they are not suitable for the rearing of animals - save the rearing of the buffalo and some varieties of hindu cattle - seem to be placed under correspondingly greater pressure by men to become suitable for such activities. These climatic conditions cover, principally, parts of the Amazon and Orinoco basins and the western slopes of the sub-antarctic Andes. However, because of its thermal characteristics this last region is more suitable for European cattle breeds.

3. Climatic factors in the Latin American environment

Not a great deal of scientific research has been done into the influence of human activity on the Latin American climate but such influence will normally be exhibited in some areas by an irrational use of natural resources caused by the creation of new and ever greater quantities of renewable artificial resources. The most extensive

and irreversible changes have occurred in those areas bearing fragile ecosystems where the geometrical and physical structures of the artificial biosphere turn out to be very different from the natural structures. The large area covered by the rain-forest and hygrophytic forests by monsoon parklands and savannas in tropical, sub-tropical and temperate semi-arid regions and by shrub deserts furnish a wide range of such examples. Analysis of these examples allows inferences to be drawn about the way in which such changes as have been made can affect local and regional climate.

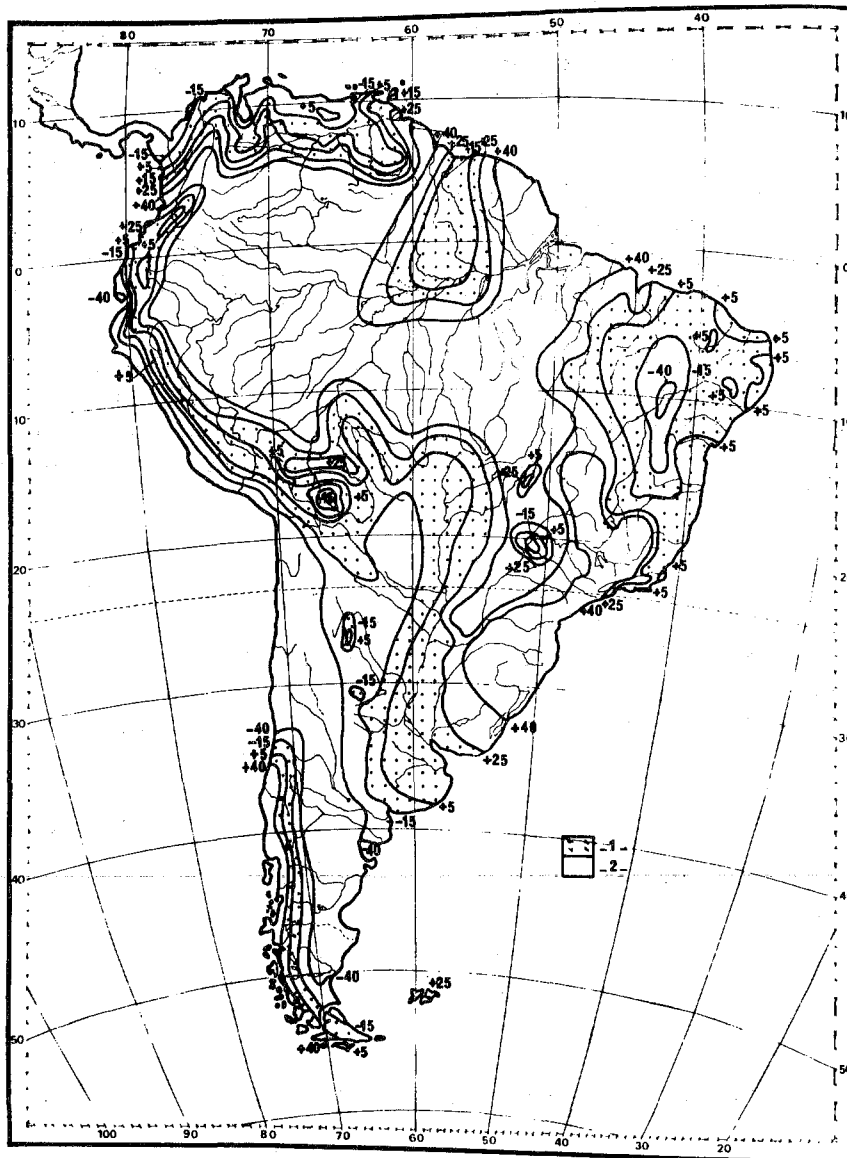


Figure 4. Natural vegetation types in South America. (1) Grassland and range lands. (2) Other vegetation types. +40 to -40, Thornthwaite's hydric indexes. Source: 8, 9.

3.1 Changes in rain-forests and tropical humid forests

The rain-forests and tropical humid forests in South America constitute the most extensive belt of this type of vegetation on the planet and are to be found in the Amazon basin and in part of the Orinoco and Tocantin river basins in the Cauca, Magdalena and upper Uruguay basins and in the Parana basin and in the basins of certain of its important tributaries, e.g., the Paraguay, the Pilcomayo and the Bermejo. These areas have very different floristic patterns, soil types and relief features which determine the ecosystem stability and its resistance to degradation. The whole area may be broadly divided into the following categories: mountain rain-forest and humid forest, highland rain-forest and humid forest and lowland rain-forest subject to periodical floods and areas of coastal mangrove swamps.

3.1.1 Mountain rain-forest and humid forest

The mountain rain-forests and humid forests have over a long period been subject to substantial man-made pressures. At first the native cultures from Andean populations and then the European settlers installed population groups whose natural means of advancement lay across mountains, woods and trees; these population groups brought with them their traditional annual crops of maize and corn. The unstable local environment forced these population groups, better used as they were to more agriculturally developed areas, into a nomadic agricultural system (shifting agriculture) which had an irreversible and destructive effect on the original forests 11,12. Statistics which illustrate these remarks are given in Tables 2 and 3, the latter providing a comparison with the more stable ecosystems in the Argentine Pampas region 13.

The stripping of wood from this type of forest was more selective and individually based because the structure of the area favoured neither mechanical transport nor development by way of straightforward destruction. Nonetheless even this restrained usage had the effect of impoverishing the ecosystems of very valuable species; the latter lost seed sources whereby they might renew themselves naturally. By way of example of this mechanism at work we would mention the near-extinction of varieties of cedar and oak.

3.1.2 Highland rain-forests and humid forests

Such forests in areas which are gently rolling and not subject to flooding, are relatively extensive in Latin America. These particular areas are subject to the greatest danger of being changed by man by reason of the extent of their surface area and ease of access for high-power machinery and for development of through roads.

The five million square kilometres covered by these forests in Brazil and neighbouring countries were up to 20 years ago almost impenetrable and inhabited by fifty to sixty thousand aborigines. By the 1980's the same area will be linked with all surrounding countries through nearly 30 thousand kilometres of roadway with bridges over minor rivers and ferries across the widest. The roads will be in the middle of a 70 m swathe to be cut through the rain-forests and there will be a 100 m area on each side which will be reserved for agricultural and farming development.

Table 2

Annual rates of soil erosion in relation to vegetative cover type and land form in the humid tropics, summarized from several sources [11]

Land form and vegetative cover type	Annual rate of erosion	
	mm	t/ha
<u>Almost flat</u>		
cotton	4.00	80
annual field crops	1.60	32
pasture, dense	0.10 - 0.50	2 - 10
pasture, open	1.00 - 10.00	20 - 200
<u>Undulating, moderate slope</u>		
natural forest tree plantation (teak)	0.01 - 0.50	0.2 - 10
- wide spacing, mixed understorey	0.10 - 0.50	2 - 10
- dense, no understorey	1.00 - 8.00	20 - 160
<u>Moderate to steep slope</u>		
natural forest	0.50 - 2.00	10 - 40
shifting cultivation during cropping years	30.00 - 60.00	600 - 1200

In Table 4 details of these proposed constructions are shown [14]. Already in this area great swathes covering thousands of hectares can be seen with savanna produced by mechanical deforestation to be used for livestock or farming purposes.

Sioli [15] has estimated that 4 million square kilometres of the woodlands within Brazilian boundaries will contain the equivalent of 10 per cent of the CO₂ content of the atmosphere; this calculation is based on a primary production of 600 tons of dry matter per hectare representing 300 t. ha⁻¹ of carbon. If, on the other hand, we accept [16] that the annual production of tropical rain-forest throughout Latin America represents an increase in dry matter of between 30 and 50 t. ha⁻¹, we may conclude that the woods and trees of tropical Latin America represent on an annual basis a fixing by photosynthesis of between 1 and 2 per cent of all CO₂ in the atmosphere. However, the destruction of present day tropical humid forests by burning leads to a savanna with an impaired photosynthetic capacity. Assessment of the reduced

Table 3

Annual rates of soil erosion in relation to vegetative cover type and land form in Pampa Region, Argentina 13

Land form	Station	Annual rate of erosion t/ha		
		pasture	winter crops	summer crops
Almost flat	Dolores	0.45	0.93	1.23
	Junin	0.32	0.68	0.89
	Anguil	0.29	0.62	0.82
	Bahia Blanca	0.28	0.60	0.79
Undulating, moderate slope	Tres Arroyos	0.56	1.17	1.55
	Rosario	0.88	1.85	2.44
Moderate to steep slope	Tandil	4.10	8.66	11.40

photosynthetic capacity will require intensive study similar to that carried out for the tropical rain forest in Costa Rica 17.

The resulting savanna may well come to an equilibrium as disclimax with low fertility (between 8-10 t. ha⁻¹) and fertility replacement on the soil will be much slower than the present rate provided by the rain-forest. The process thus arrived at is irreversible since not only will fertility conditions change and the seed bearing plants will have disappeared, but also the elements of both water and energy balances in the soil will change substantially 13. It has been shown 19 that the near-surface soil temperature in a clearing of the forest covered with short grass averages a maximum of 46 deg C in the hottest month (October) and 43 deg C in the coldest month (January).

It has also been calculated that under similar conditions the soil will absorb some 22 per cent of the daily energy total of 423 cal cm⁻². If it is borne in mind that the surface soil under the rain-forest will remain at a constant temperature or 23-25 deg C, 21, 29 that there will be no absorption of solar energy and that the temperature variation will be very small, it will readily be understood that in the conditions pertaining in the man-made savanna, the fertility of the soil will rapidly be depleted because of the death of micro-organisms (microflora and microfauna). Furthermore under such conditions the seeds that would have provided new plants will also die.

Table 4

Roads built and planned in the Amazonian Basin. Source: 14

Road Number	Starting Point	End	Length	Start	Planned Finish
BV8	Brasilia	Caracas	5 758	1973	1976
080	Brasilia	Manaus	2 227	1970	
163 (o 165)	Cuiaba	Santarem	1 747	1970	1974
153 (o 165)	Santarem	Surinam	600	1972	1977
BR 230, 404, 317 y 364: Transamazonica	Joao Pessoa	Peru	6 368	1970	1974
010 (asfaltada)	Recife	Peru			
(210) Perimetral Norte	Belem	Brasilia	1 901	1958	1973
	Macapa	Mitu (Colombia)	2 465	1974	1978
307	Cruzeiro do Sul	Cacui (Venezuela)	1 454		1978
317	Labrea	Assis Brasil	879		
319	Porto Velho	Manaus	866		1973
156	Macapa	Guayana Francesa	684		
174	Caceres	Venezuela	2 860		
401	Boa Vista	Guyana	162		

If the transformation of the highland rain-forest is carried out through micro-agrosystems with farming crops, the results would be very much more harmful. The total loss of the fertility of the soil would occur in about three years. The lesson of the agricultural communities in Venezuela was an instructive one. These communities introduced the annual crop sesame for oil but the return on the fields went down from 700 kilos ha⁻¹ of oil in the first year to less than 200 in the fourth. The experiment took place in areas where the African Palm could have produced more than 4 000 kilos of oil per ha per year with much less damage to the soil in the process.

3.1.3 Flooding lowland rain-forest - Varzeas

Lowland rain-forests and humid forests, periodically flooded, have also been put under pressure for the production of artificial renewable economic resources. Large areas of the Amazon basin and slightly smaller areas of the Orinoco are of such characteristics. At the peak points of the floods, waters cover many square kilometres of the surrounding land on each bank of the rivers. These floods usually carry with them lime and other minerals which are important for fertilizing the soil. Under such circumstances the use of the soil during the low-water periods has usually been for the planting of upland rice, jute, sesame, beans and maize and as pastures for the buffalo and other animals.

In some cases, efforts have been made to change the natural pattern of the floods in order to improve the output from the soil. This has normally been done through the construction of dams and canals and in areas where the flood waters would otherwise have flowed into the ocean, the net effect has been to improve the output and the quality of life in the area to a quite significant extent. However, very low-lying areas that are more susceptible to flooding, need expensive drainage works to be carried out on them before they may be used for micro-agrosystems such as rice. In fact the best results will be obtained when such lands are used for various useful natural plants such as palm-tops (*carapa guianensis*) and forest stands (*Virola Surinamensis*).

3.1.4 Coastal mangrove swamps

The coastal mangrove swamps are apt to be very dense in certain parts of Latin America and are not a great deal of use because of the salt water that floods onto the low-lying regions with the high tides. Nonetheless, as the Dutch found out in Guyana, it was possible to erect dykes along the sea front that will at least keep out the water from the high tides. A system of sluices will also enable the non-saline water to escape to the sea from the rivers during the low-tides. Using this method, an important strip some 30-40 km wide - including the bottom-swamps and neighbouring lands - was drained and turned into fertile land where sugar cane, upland rice, and vegetables can be grown and where large centres of population have been developed.

These facts, as referred to above, highlight the struggle between the natural resources and renewable artificial resources in Latin America and the effect that such a struggle has on the environment, including the climate. Such facts also lead to the formulation of working hypotheses for evaluating the physical consequences that flow from differing uses of land. Particularly is this the case where we are dealing with ecosystems that are essentially fragile.

3.1.5 Micro-agrosystems in the tropical rain-forests and humid forests

Micro-agrosystems whose development in the areas of the tropical rain-forests and humid forests is consistent with the conservation of the physical structure of the biosphere may be ordered as follows:

- (a) under-shade crops or forest stands;
- (b) tree crops with associated grasses or legumes without farming;
- (c) induced savannas with natural or seeding pastures;
- (d) tree crops with farming and fertilizing practices;
- (e) dense annual crop farming;
- (f) sparse annual crop farming.

The original, natural state of the habitat will be altered least by the growth of certain crops within the shade of some of the larger trees in the area and this is something that used to be done in the mountain rain-forests and humid forests with coffee and cocoa.

Figure 5 shows a schematic representation of an hypothesis dealing with the modification of the principal elements in the energy and water balances in the biosphere. In the first place it has been assumed that the rain-forest and its undergrowth and litter are able to absorb all the short wave energy (R_g) passing through the canopy. Dense foliage at any level of the forest will act as a radiation trap. The radiation will be gradually depleted by a process of successive reflections and absorptions and may never reach the soil surface. It is partly for this reason that the albedo above the crown of the highest trees is generally supposed to be low. The amount of heat used in evaporation (LE) is high and the energy emitted from the active surface is at its lowest. The amount of sensible heat (H) is quite low and the air above the canopy, enriched by moisture, is a source of the greatest amount of counter-radiation in the systems under comparison. So far as the water balance is concerned, this may be identified as a maximum of actual evapotranspiration and a minimum of run-off (Figure 5).

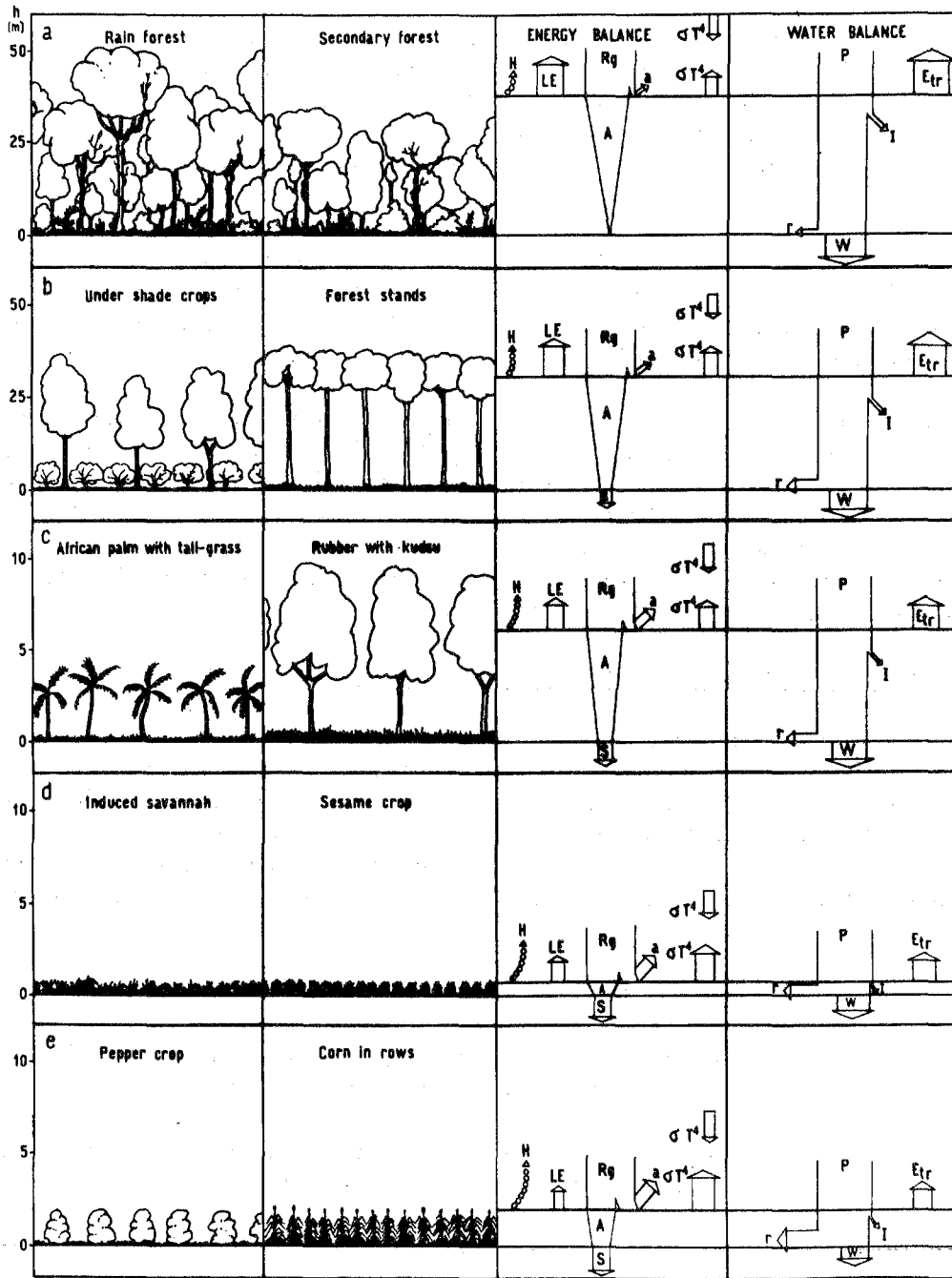


Figure 5. Ecosystems and micro-agrosystems in the rain-forests and humid forests of Latin America. (a) Secondary forest. (b) under shade crops and forest stands. (c) tree crops with tall grass and legumes. (d) induced savanna and dense annual crops. (e) sparse farming crops. R_g , global radiation; a , albedo; A , energy absorbed by the canopy; σT^4 , long wave radiation fluxes; LE , heat used by the evapotranspiration; H , sensible heat; S , heat transfer in the soil; P , precipitation; E_{tr} , actual evapotranspiration; I , interception; r , run-off; W , water storage in the soil.

It will be seen from the micro-agrosystems listed, that as we pass down the list the soil absorbs ever more energy (Figure 5bcde); the albedo, surface emission and sensible heat all increase while the latent heat of evaporation and the atmospheric emission are reduced. In dealing with the water balance, it will be noted that the run-off increases, whilst actual evapotranspiration and water storage are reduced.

It is emphasized that the hypothesis is based on the same levels of radiation for each micro-agrosystem. However, where the changes are being wrought over large areas, as in the changes at the meso-scale then it is possible that the global radiation may be varied by the changes in cloud cover.

It is important at this stage to draw attention to the theoretical work done by Molion on meso-climatic analysis [22]. This work is based on data drawn from the Amazon basin and suggests that 50 per cent of the local rainfall will be derived from water recycled by the rain-forest. If this analysis were to stand up to a practical test we would have some means of determining on what scale the cloud formations and rainfall levels would be affected by the man-made changes in the forested surface.

4. Changes in and use of the monsoon savannas

The monsoon savannas in Latin America are another area which man has tried to change for his own purposes. For several centuries these lands have been used either as agricultural areas during the rainy periods, or as areas for the development of unstable systems of animal rearing in both dry and wet seasons. People living in these areas would use the horse as the main means of communication and of transport during the dry seasons and would use the canoe for similar purposes during the wet season.

The changes that man has tried to introduce in these areas were due to:

- (a) the irrigation of the area during the dry season in order to extend the period of agricultural output throughout the year; and
- (b) the creation of reservoirs of water during the wet periods in order to offset the effects of the dry periods.

~~There are large areas in most countries irrigated by these methods.~~

One example of the effects of building water reservoirs during the wet season is provided by an experiment carried out in Venezuela [23]. The area affected, the so-called "Modulos del Apure", covers more than 1 million hectares with little in the way of hills; there are in the area experimental sub-areas; the Bruzal area with 65 000 ha and Mantecal with 77 000 ha. The "Modulos" were constructed, as shown in Figure 6. An area some 2 to 10 thousand hectares was surrounded with earthwork-dykes to stop the surface water flowing away. It was thus possible to flood an area some 3.4 km each side of the dykes once the water level had reached about 60-30 cm at its deepest point. When the rain stopped, the water would retreat from the flooded area (through the natural processes of evaporation) and would leave behind a broad swathe of

fertile pasture lands. Even the area that was flooded would bear hydrophytic grasses of use for feeding cattle. There was also a system of sluices that would allow the regulation of the level of the water within the model both during and after rainfall. The effect on the environment has been substantial. Although there are no quantitative studies on the climatic effect, it seems clear that during dry seasons there will be higher absorption of the radiation, a lower albedo, increased energy consumption through evaporation and a perceptible reduction in the sensible heat. The indirect effects of this change in the climate have been more obvious. There are large pasture lands available for use during the dry season and there have been noticeable changes in the wildlife population. There is still a wide range of matters that need serious investigation, and it may be that not all of these will be positive in nature like some related to human health [24]. However, it is already apparent that the reduction in the climatic extremes in the region has led to a 50 per cent reduction in the number of types of vegetation found locally. The ecosystem is expected to reach a point of stability in 5 year's time but it remains to be seen how useful the new dominant species will be in practice [25].

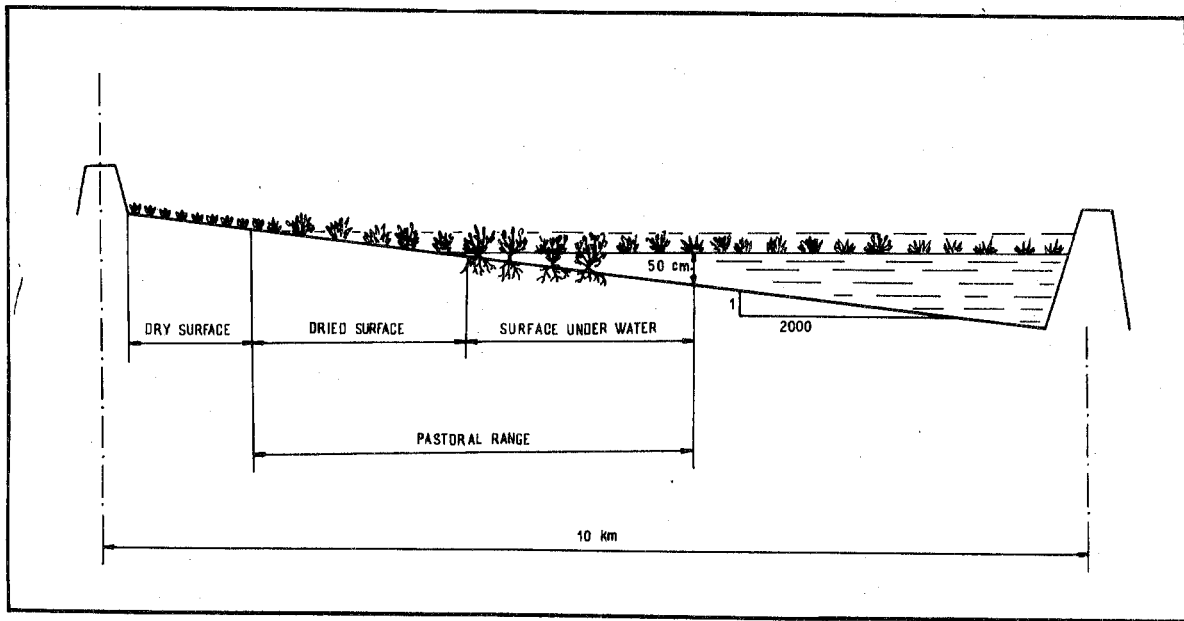


Figure 6. Simplified outline of the Modulos del Apure scheme.

5. Changes in and the use of semi-arid regions

The semi-arid areas occupy large parts of Latin America and are to be found amongst all the various temperature régimes from equatorial to cold. For the purposes of this paper semi-dry areas fall within the -25 to -15 range using the Thornthwaite hydric indices. This is particularly the case in the temperate climates where the great variability between dry and wet years means that farming practices must follow those of dry-land farming. However, it should also be noted that the driest monsoon savannas in Ibero-America have hydric indices within the same range. In several countries xerophytic forests were deeply degraded by industrial deforestation or fuel use.

In these areas human action, seeking to provide more renewable artificial resources, has adopted techniques to optimize the use and management of water. However, where these areas were agriculturally unstable, they were stripped of their plant cover by overgrazing and there has resulted a lower regeneration of trees and the invasion of thorn shrubs. Thus it is that important species of trees have had their chances of re-growth greatly reduced. In certain conditions, the trees are fighting for their survival against an unproductive cattle herd.

When irrigation was possible, the fields were opened up to the growth of plants like cotton, sugar cane, tobacco, vegetables and fruit. This change did not have the same devastating effect on the vegetation in the woods as was wrought by the felling of trees and overfeeding on the land. The physical effects were an increase in albedo, a reduction in the amount of energy consumed through evaporation, and an increase in the temperature. In consequence evapotranspiration is reduced and so is the surface flow of water. This change in the conditions over large tracts of the land could lead to changes in the air-mass above; such changes would probably be towards drier air with higher surface temperatures and increased convection. When irrigation was provided on much smaller areas, precisely the opposite effects were noted but they were only of local importance.

In the temperate semi-arid areas, large parts of Latin America have been given over to extensive farming and cattle rearing because the xerophytic forest would naturally give way to bushes and sparse pastures. It was particularly the case in the Argentine that the improvident use of such lands resulted in the creation of serious wind erosion and the other harmful effects referred to in Section 1 above. After two decades of rational treatment of the soil, all the eroded areas have fully recovered and are now being used at their most productive. The methods used during this period included alternating between agriculture and cattle rearing, the use of machinery for the light work on the soil and, especially, the introduction of weeping love grass (*eragrostis curvula*).

The introduction of the weeping love grass leads to the surface being more efficient physically, than it was before the erosion took place. These grasses now cover 600 000 ha forming a thick mulch with its dead leaves, and this has the effect of almost wholly cutting out direct evaporation from the soil. It also has the effect of reducing wind-generated soil evaporation as well as the surface runoff after rainfall. It has been calculated that with this grass, there will be 200 m³ more water per hectare for use by the plants and consequently there will be more CO₂ fixing 8.

Fallowing is another system that is used in these areas in order to obtain an increased efficiency in the use of the water in the soil. This system encourages the penetration of water into the soil and also reduces losses arising from the transpiration of water by weeds and wild plants, the water so saved being available for the next crop period. Experiments that have been carried out show that this method may lead to the retention of up to 30 mm of water per metre of depth than was

the case in the fields that were not so treated; there is also a 43 per cent increase in the winter wheat harvest [26]. However, Fagioli [27] noted that there was a large water loss from fallow lands during the summer months and therefore short fallows were advised in the autumn and winter for summer crops. It should be noted that this type of change is not one that can be spread over large areas since it is only a part of the crop-rotation process. On the other hand, any soil workings that involve ploughing will run the risk of erosion particularly where there is poor sub-soil structure.

A micro-agrosystem that consists of a surface area covered with weeping love grass, will have the following regional effects: reduction in albedo and loss of surface water together with lower sensible heat and a reduction in the level of evapotranspiration. The consolidation of the soil combined with the introduction of nutrients and organic matter means an increased water-retention capacity and soil waterstorage. The effects on the air mass lying above the region may be described as follows: a relative drop in temperature, increased humidity, and lowering of thermal turbulence in the boundary layer.

6. Changes in and use of arid regions

In agricultural terms, dry regions are regarded as those where agriculture is not possible without irrigation. This definition embraces a wider area than the indices set out by Thornthwaite who specifies a value below -40 [10]. The regions that fall within our definition form a substantial area in Latin America.

The arid regions will, under natural conditions, provide surfaces covered with bushes, xerophyte grasses and large shrubs, not to mention pure deserts. All these areas have been deeply changed by man. These changes have by turns been harmful and beneficial from a human point of view.

6.1 Beneficial changes

Irrigation has been the most efficient means of changing the dry regions because it has permitted agricultural production throughout the whole year in what were virtually sterile lands in the tropical and sub-tropical regions. In the corresponding areas with a temperate climate production is possible through the summer, whilst in semi-arid monsoon areas, production is possible in the dry season. The relative importance of irrigation in the Latin-American countries can be seen in Table 5 which shows not only the area that has been irrigated but also rough estimates of evapotranspiration and of the heat used in the process.

In order to arrive at this estimate, an irrigation period of 6 months was considered in respect of each country - even though the actual period in the tropical and sub-tropical countries may be greater; an average evapotranspiration of 5 mm was used in respect of Mexico, Argentina, Chile, Bolivia and Uruguay; a figure of 7 mm was used for the remaining countries. It will be noted that there are already in Latin-America more than 125 000 km² of land that has been irrigated. The capacity of the area is such that the figure could be tripled. Such a surface area would imply an annual evaporation of almost 130 000 hm³; in turn this figure is the equivalent in terms of energy to the absorption by the atmosphere of 7.8 x 10³ megacalories of latent evaporation energy which would in due course be released by

condensation. If it were not thus, the excess water taken up would run off to sea across the surface. By the nature of the estimates put forward here, where the irrigation period exceeds 6 months, the true figures may well be larger than those suggested.

Table 5

Surface area irrigated and estimate of the volume of water evapotranspired, and of amount of heat used in the evaporation in one agricultural year (6 months) for 20 countries in Latin America in order of area irrigated. Source: [7].

Order	Country	Hectares irrigated x1 000 ha	Evapotranspiration hm ³	Heat consumed in the evaporation	
				Mcal/ha	Mcal total
1	Mexico	4 816	43 344	5.40 . 10 ⁶	2.60 . 10 ¹³
2	Argentina	1 820	16 380	" " "	9.83 . 10 ¹²
3	Chile	1 280	11 520	" " "	6.91 . 10 ¹²
4	Peru	1 150	14 490	7.56 . 10 ⁶	8.69 . 10 ¹²
5	Brazil	980	12 348	" " "	7.41 . 10 ¹²
6	Cuba	730	9 198	" " "	5.52 . 10 ¹²
7	Ecuador	510	6 426	" " "	3.86 . 10 ¹²
8	Venezuela	320	4 032	" " "	2.42 . 10 ¹²
9	Colombia	285	3 591	" " "	2.15 . 10 ¹²
10	Dominican Rep.	135	1 701	" " "	1.02 . 10 ¹²
11	Guyana	122	1 537	" " "	9.22 . 10 ¹¹
12	Bolivia	120	1 080	5.40 . 10 ⁶	6.48 . 10 ¹¹
13	Haiti	70	882	7.56 . 10 ⁶	5.29 . 10 ¹¹
14	Uruguay	58	522	5.40 . 10 ⁶	3.13 . 10 ¹¹
15	Paraguay	55	693	7.56 . 10 ⁶	4.16 . 10 ¹¹
16	El Salvador	33	416	" " "	2.49 . 10 ¹¹
17	Surinam	30	378	" " "	2.27 . 10 ¹¹
18	Costa Rica	26	328	" " "	1.97 . 10 ¹¹
19	Panama	23	290	" " "	1.74 . 10 ¹¹
20	Trinidad	20	252	" " "	1.51 . 10 ¹¹
	Total	12 583	129 408		7.76 . 10 ¹³

We should perhaps note here some remarks by Sinizina *et al.* [24]. The 2 million km² of irrigation that at present exist on the Earth have the effect of reducing the Earth's albedo by 0.03 per cent. When we consider that the reduction in the albedo of 1 per cent will produce a temperature increase of 2.3 deg C in the Earth temperature, it will be apparent that the irrigation works on the Earth are capable of increasing the temperature by 0.07 deg C. Over the coming years Latin America will be responsible for almost 10 per cent of this increase.

Even if this change has to be seen in terms of its effects on the Earth's macroclimate, it is in local and regional terms that its effects are most dramatic. In the temperate arid zones, as in the south of Mendoza, the Rio Negro, and in Argentina, it has been shown that the irrigation of 60-100 thousand hectares will increase the average frost free period of 30-40 days, and will reduce the severity of such frosts as do occur. At the same time changes in temperature and humidity are noticeable up to 1 600 m in the lower troposphere.

Great attention should be paid to the effectiveness of the irrigation systems in the future when this form of improvement is decided upon for the arid areas, particularly in projects that are not yet underway. Damage may be done, e.g., by the use of too much water, which would limit the extension of the irrigated lands. Certain developments which have been of great value locally have been fully exploited for economic reasons. Examples such as the trickle or drop irrigation or the sprinkler irrigation systems spring to mind. There are other developments which help to solve local problems, but which are of little impact as factors for change on the meso- and macro-climatic scales. Examples are the use of plastics or other waterproofed products and collecting towers, water reservoirs for animals and "harvest water systems" for oasis agriculture.

6.2 Harmful changes

Latin America has seen the same serious mistakes committed in relation to the use of its dry regions as were committed in other continents. The use of what scanty vegetation there was was either as a fuel or as an element in the production of carbon, the over-cropping by voracious breeds and the protection of flocks from the carnivores that in the old days used to control the population of the herbivores and rodents - all these factors combined to ensure the destruction of the plant cover. This in turn lead to the erosion of the topsoil and the encroachment of the desert. The sheep, in growing ascendancy over the steppes, left the soil entirely open to the blasts of the strong winds. Once the sand-dune is firmly established on the base of impacted earth, the wetness of the scarce rains is insufficient to allow the majority of plants to take root; even if we assume that this were to occur, the combination of rapid drying, extreme temperatures, or new accretions of sand would act to limit the extent of its life.

Such phenomena are typical of large areas of the Argentine Patagonia where the tongues of erosion follow the lines of the winds that blow strongly from the west across the transverse sub-Andean valleys. The edges of the sand go forward over the impacted soil in a typical process of desert-making.

A somewhat similar process may be seen at work in the west of Argentina, where over the last 15 years there has been an intense process of desertification at work; the process has been centred on the dry N - S valleys lying across the mountain ranges around the western side of the pampas. An important group of sand dunes to the highest areas in the north of these valleys on the exposed western flank of the mountains, seem to follow the line of the regional cyclonic winds. Figure 7 shows a comparison of the content of water taken from the Fiamala Valley dunes against that taken from compacted soil; it seems that the former area is destined to be covered with sand to the extent of some 1 000 ha. It will be seen that whilst the sand-dunes (to a depth of 1 metre) are as dry as if the sand had been processed for 48 hours at 100-105 deg C, those samples from consolidated soil (even

though they are a long way from any irrigation sources, e.g., Tinogasta) are sufficiently humid to support xerophyte plants. It should be mentioned that, so far as the observations are concerned, it was not possible to obtain readings deeper than 80 cm in impacted earth at Fiambala, 90 cm at Tinogasta in the same type conditions, and 1 metre in the dune; the reason for this was that the water did not penetrate any further than these depths in the field tests.

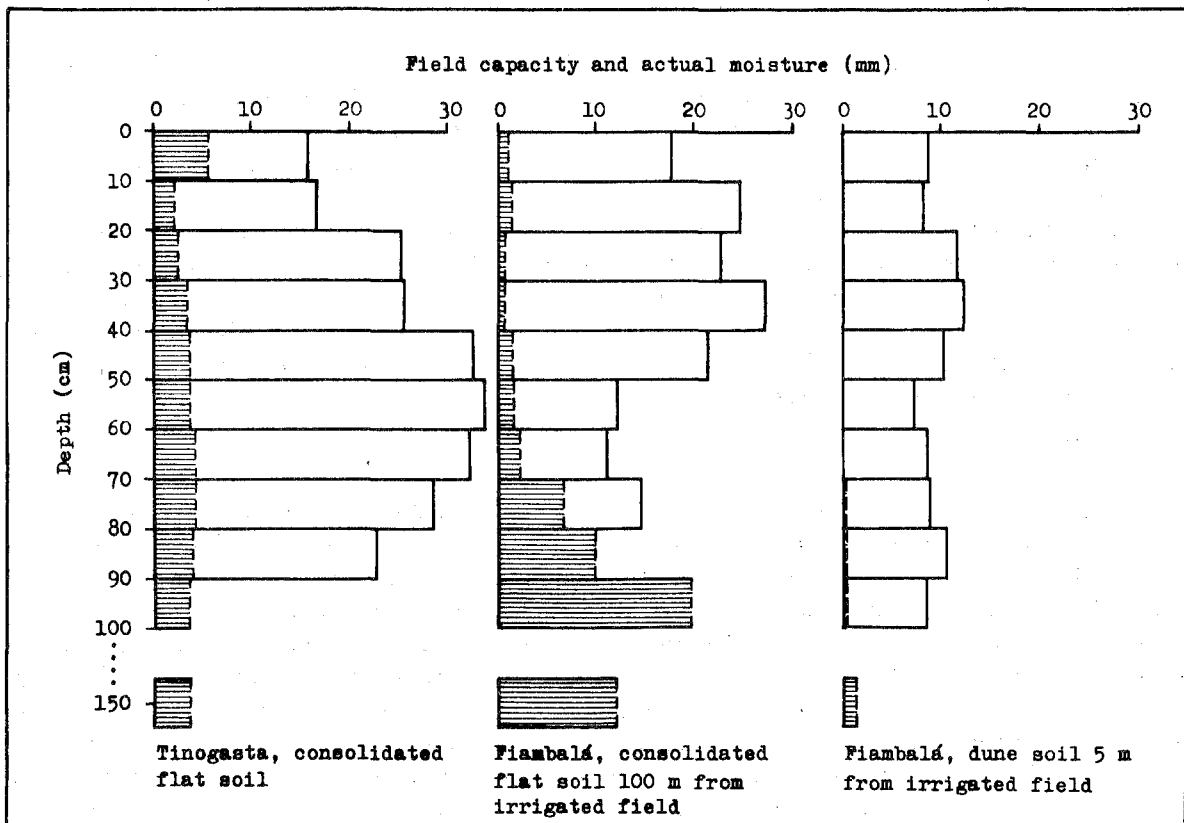


Figure 7. Soil moisture on 15/12/1977 (hatched area) and field capacity (mm) (total area), in different depths of consolidated flat soils and dune soil in the Fiambala valley. Tinogasta is some 40 km to the South of Fiambala, at the exit of the valley of the same name.

Despite the fact that local experience suggests that this phenomenon may be attributable to over-grazing and wood clearing, it might perhaps be worth considering to what extent the large-scale decline in plant covering in the middle of the country and in surrounding countries also contributed. For this purpose it would be necessary to show that the surface conditions (through the increased albedo and the transfer of sensible heat) increased the temperature of the boundary layer of the continental air masses which form particularly in the centre of the country and in the south of Brazil and Bolivia and in the west of Paraguay. Such conditions would in the summer increase the extent of the continental thermal low in South America as well as the speed of the winds that blow up from the south along the western flank of the system. A further point that would require clarification would

be whether this system would lead to an increased inflow of relatively cold wind from the south; this wind would be blowing in from the ice caps that would be relatively warmer, and there would therefore be a tendency to reduce the temperature gradient, and from this reduction would come greater stability and less local precipitation. If these hypotheses were substantiated, it would be clear that the intense process of desertification that is at present occurring in those Andes valleys that are open to the flow of air from the south, would only be a part of the general destruction of the environment by mankind in central South America between latitudes 20 and 40° S.

7. Conclusion

The facts set out above reflect a series of observations on the actions of man in exploiting renewable natural resources and changing them to obtain artificial renewable resources, namely, forestry, agriculture and animal rearing in order to satisfy present and future needs. From these actions the climate on the micro-, meso- and macro-scales appears to be affected although as yet there has been little systematic experimental work done to assess the changes and their consequences.

The great increase in the population of Latin America, the great potential wealth of the area and the fragility of its biomass and ecosystems - these factors require us to try to quantify, in all the development projects, the effects on the microclimate, and the relation of the microclimate to the regional and macroclimates.

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CLIMATIC VARIABILITY AND LAND USE

An African Perspective

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1. Introduction

Climatic variations are known to have occurred throughout geological times and must be expected to occur in the future. Such variations have influenced the fortunes of mankind since his appearance on the Earth. The changes that took place in the societies in Mesopotamia and the Roman Empire are not totally unconnected with climatic variability, emanating from the shortages of basic food commodities. In Africa, archaeological, geomorphological and historical evidences show that the Sahara Desert has experienced some periods of much wetter climates than at present; people, wild and domesticated animals had been able to survive in many areas of the present day Sahara Desert /1, 2/. On the margins of the desert, kingdoms waxed and waned as climate varied; these included Songhai, Mali and Ghana on the southern fringes of the Sahara.

In the more recent past better communications have given world-wide publicity to the extremes of climate in the areas adversely affected. Such was true of the 1968-73 Sudano-Sahelian drought /3/. These disasters provoked sympathy from people in distant areas and efforts were made to find out the causes and effects of such climatic events.

The 1968-73 Sudano-Sahelian drought was uniquely effective in emphasizing the importance of climatic variability as a major influence on the economic activities of man. Drought, floods, hurricanes, excessive snowfalls, to mention a few, affect human economic activities ranging from agriculture to air transport and tourism. In the case of Africa, where most people are still peasant farmers, the impact of climate on economic activities is most felt in the fields of pastoralism and

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agriculture. The areas most adversely affected in times of crises are the desert and the areas marginal to it, i.e., the Sudan and the Sahel zones; this is well illustrated in Figure 1.

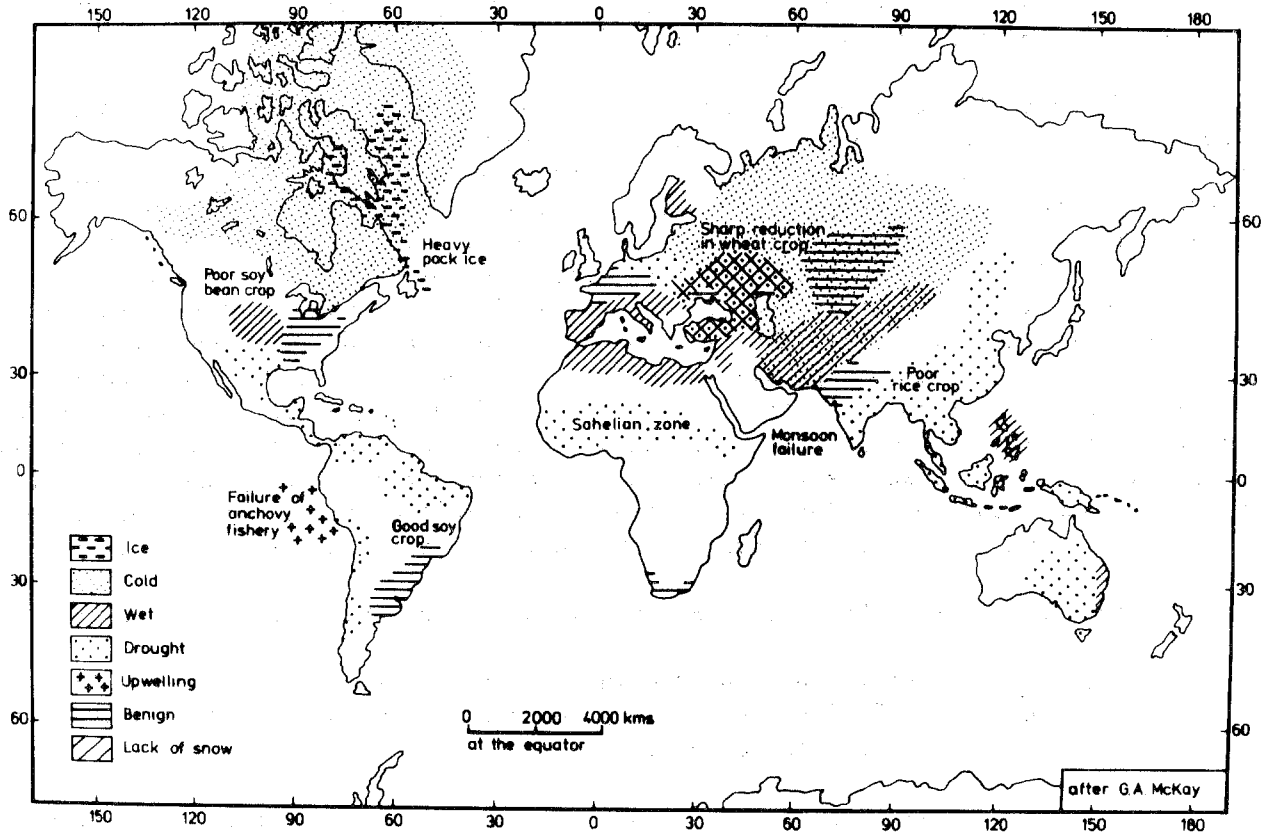


Figure 1. World climate variations in 1972

This paper therefore attempts to highlight some of the events in Africa, mostly south of the Sahara, especially within the last few hundred years; evidence will be adduced to show the effects of climatic variability on land use characteristics under varying conditions, and also to show the resultant effects of man's impact on the environment. In doing this, greater emphasis will be laid on the areas marginal to the desert. These areas give a false sense of security to human occupation during periods of successively wet years but are highly vulnerable in periods of drought.

One fact that quickly becomes clear is that as regards the significance of climatic variations for land use, at least for the tropics, most attention needs to

be given to rainfall variability and much less to other elements such as radiation, temperature and soil moisture. Some of these other elements are also important to land use in a more restricted sense, and they will be touched upon briefly in this study. Adequate supplies of light, heat and water are required for crop production, and for the production of the plant biomass on which successful range management depends. Furthermore the needs and tolerances for light, heat and water of the various cultivated plants in the tropics differ 4.

In general with the exception of the highland environments in East Africa, and the more northerly sub-tropical areas like North Africa, temperature and its variations do not play a very significant part in land use considerations. At heights where most crops are raised, the highlands of Eastern Africa (Ethiopia and East Africa, 1 500 - 2 800 m) enjoy moderate or even cool temperatures all year round without experiencing the growth-arresting winter temperatures of higher latitudes. Above 3 000 metres, frequent night frosts are a limiting factor on cultivation in regions where rainfall is still sufficient to raise crops 5. Secondly there is also altitudinal zonation emphasizing the role of temperature in controlling land use to a certain extent. In the highland areas of Eastern Africa low enough temperatures have led to the planting of crops normally associated with temperate or sub-tropical latitudes, like wheat, barley, oats and pyrethrum (usually above 1 500 m). However, temperature variations still play only a small part and should not feature much in a discussion of climate variations and land use, at least in the tropics.

The questions to be asked next in this paper are therefore as follows:

- (a) How much do we know about climatic variability with specific reference to rainfall? Are the existing records sufficient to serve as a basis for meaningful conclusions?
- (b) What is the importance of water availability for pastoralism, crop agriculture, and for other forms of land use?

2. The nature of climatic variability in Africa

As already stated, for most tropical countries, and certainly for tropical Africa climatic variability can be virtually equated with rainfall variability. The high incidence of destructive droughts can also be directly associated with the collapse of pre-existing land use systems as in the case of the Sahelo-Ethiopian drought, which extended to East Africa as well (especially Kenya and Tanzania).

There are still several imperfectly answered questions that were put forward during the 1976 United Nations Desertification Conference:

- (a) What is the present state of knowledge about secular or long-term shifts of climate?
- (b) To what extent can climatic variations be attributed to man's activities?

- (c) What are the prospects for longer-term (seasonal and longer) forecasts?
- (d) What is the likelihood of significant human amelioration of the present conditions? 6

Of the above questions an attempt will be made to provide some answers for (a) and (b) with special reference to tropical Africa, where dry climates are extensive (Figure 2). Other papers prepared for the World Climate Conference address themselves to the other two and several similarly pertinent questions.

There is emerging a body of knowledge on the climatic variability in the Sahara Desert and its margins since the Pleistocene 1, 2, 7. East Africa also provides useful information 8, 9. Our discussion in this paper will focus mainly on the past few hundred years in which human activity has been intensified due to increases in population and in human activities, but we shall first attempt a brief look at the more distant past in order to give some perspective.

Starting from about 6000 BP the Sahara experienced a moister climate, prevailing between 6000 and 4700 BP 2, 10. Desiccation of the climate possibly began well before 4700 BP but the impact was apparently delayed due to higher water table and extensive oases. Such sites provided adequate habitats for wild life, domesticated animals, human beings and their crops. The period between 4700 and 3700 BP was arid. Until 1000 BP there was a fairly regular alternation of moist and arid phases with durations of 700 to 800 years. The area thus became successively drier, but not as dry as today, during the Roman occupation in North Africa, about 100 B.C. The period between 1200 and 1550 A.D. showed evidence of a moister climate 11.

Details of the levels of Lake Chad also provide a good basis for estimating the climatic variability in the southern Sahara in the period 12000 to 2500 BP.

Table 1

Hydrologic history of Lake Chad

Date	Description	Surface level (a.s.l.)
12 000 - 7000 B.P.	Megachad, the pluvial transgression, peak at about 1000 B.P.	Just below 320m
7000 - 5000 B.P.	The Lagoonal Period; Lake Regression	Less than 287m
5000 - 2500 B.P.	Lake Chad: Regression	280m

Source: 12

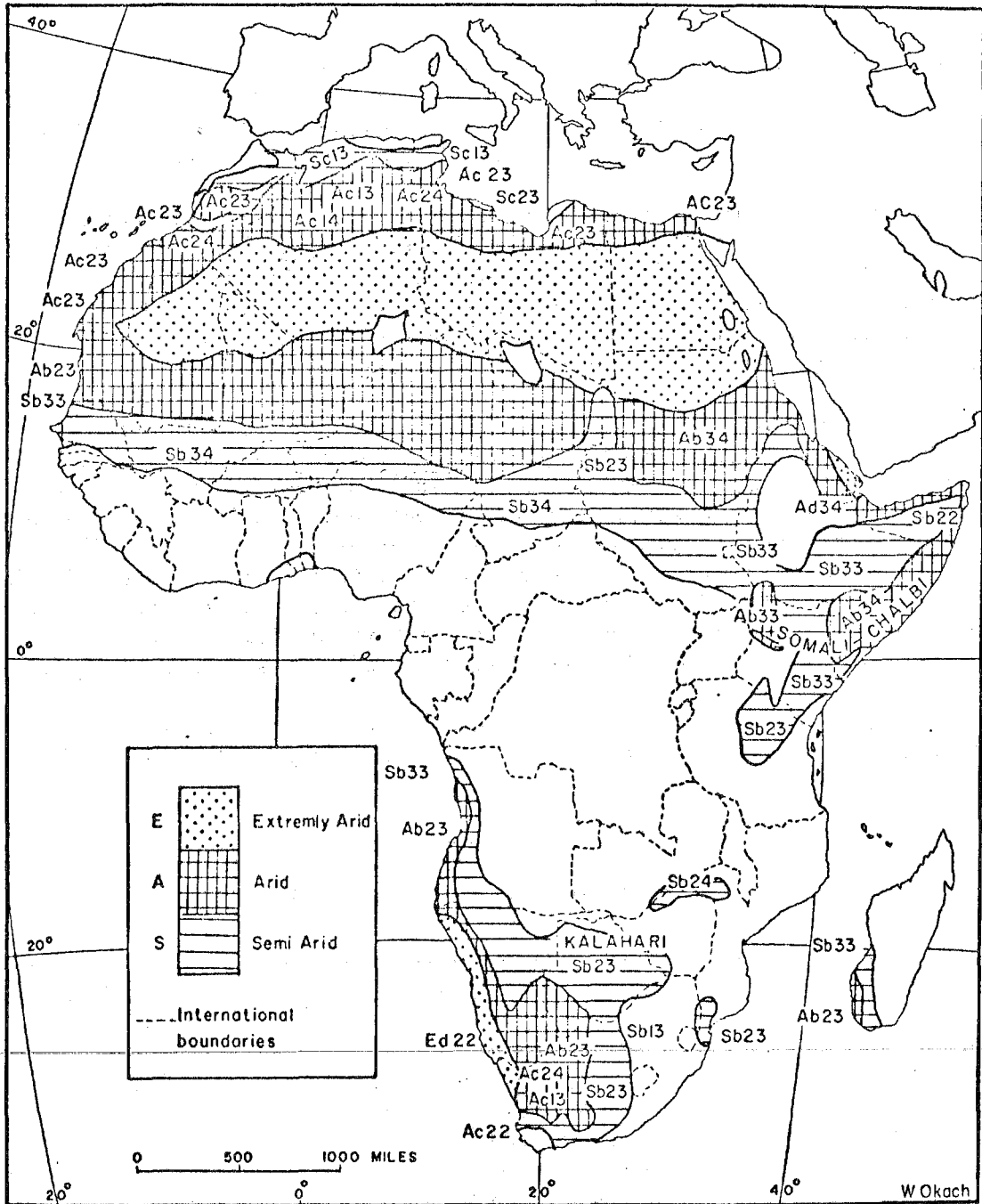


Figure 2. Arid lands of Africa

In the more recent past instrumental records are available to show the fluctuations in the levels of the lake, thanks to the works of the French administrators 12. Figure 3 shows the fluctuations in the lake levels for the past 100 years.

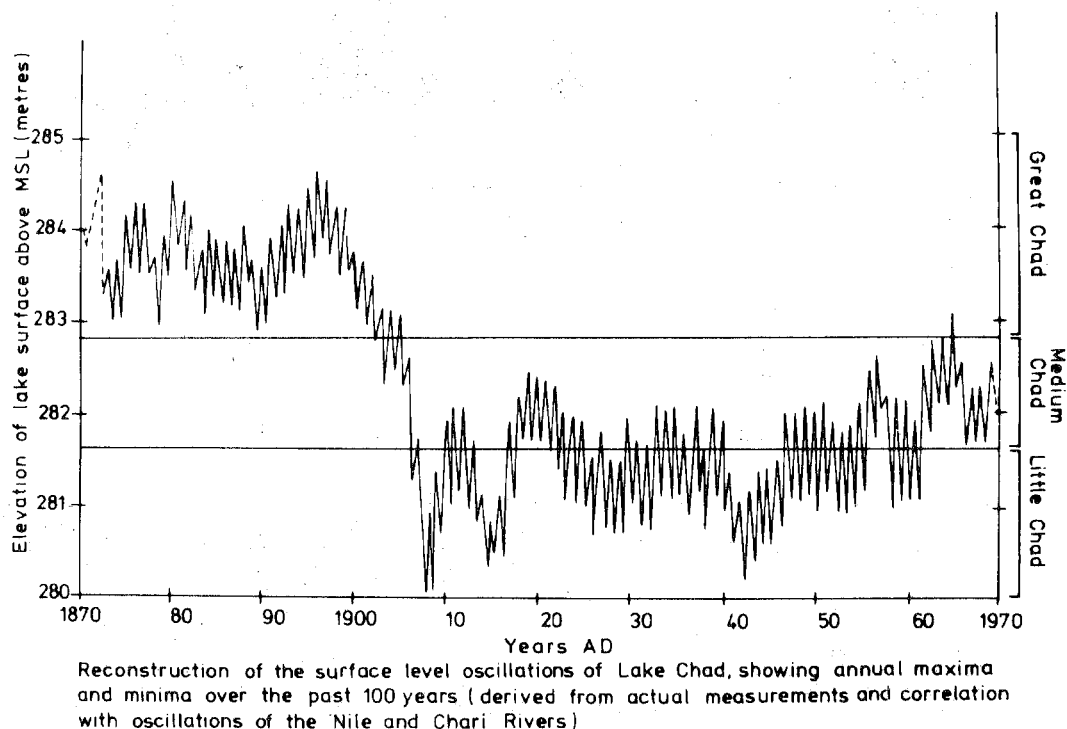


Figure 3. Fluctuations in the levels of Lake Chad 12.

2.1 Rainfall variability

If the fluctuations in the levels of Lake Chad can be taken to indicate climatic variability in the surrounding areas, it can be concluded that rainfall has shown a dramatic variability, which should have affected land use practices from time to time.

Records show that rainfall in these zones is highly variable. In central Tunisia, for example, steppes at Sidi Bou Zid had a mean deviation of precipitation from the average of 30.6 per cent in the period between 1932 and 1963. In the year 1969 an absolute maximum of 312 per cent of the norm was reached (Figure 4). Similar patterns have been recorded further south in the Sudano-Sahelian zone (Figure 5).

Annual mean 247mm

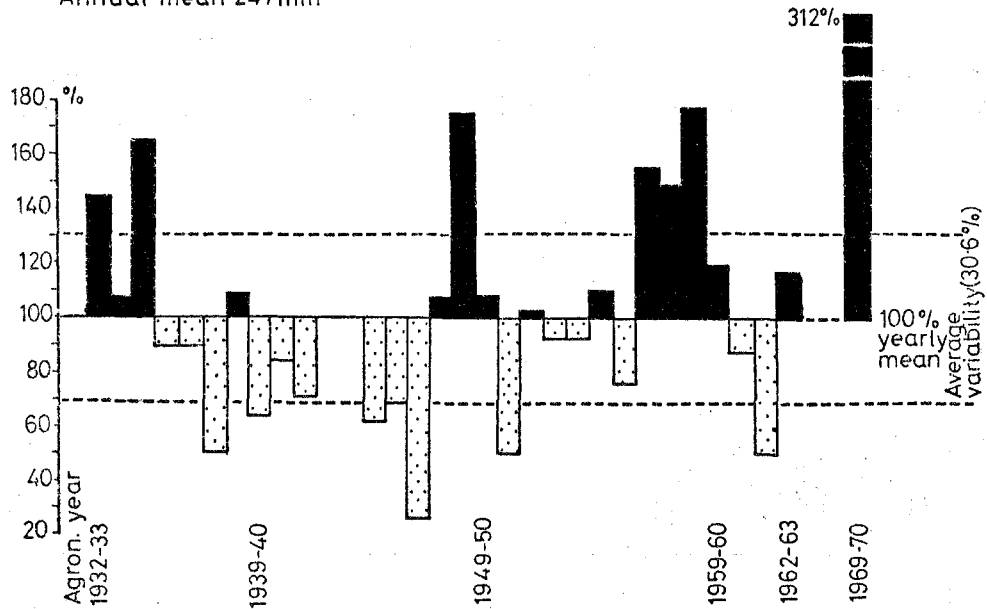


Figure 4 Variability of rainfall at Sidi Bou Zid

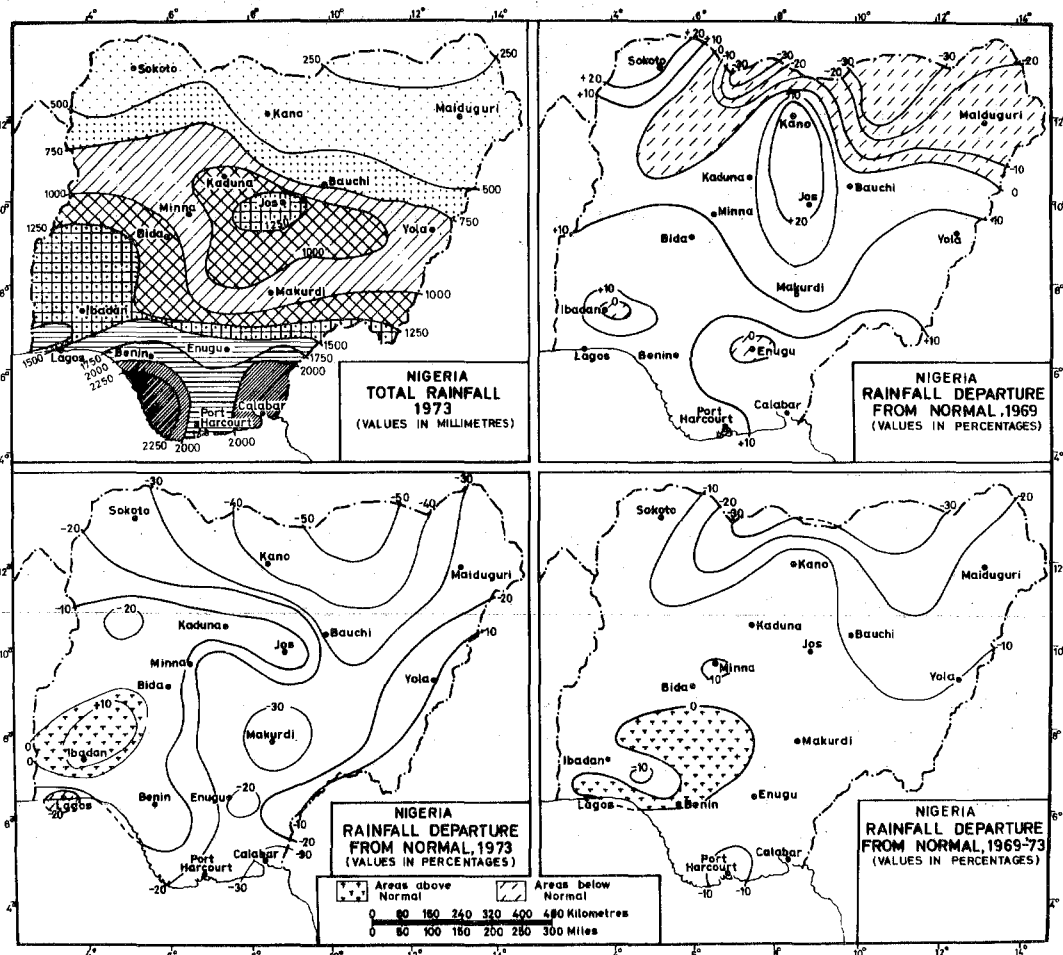


Figure 5 Variability of rainfall in Nigeria 1969-73

Table 2 shows the situation in Gao (Mali) in the period 1966-1973 as compared with the 1931-1960 standard values. Since observation started in Gao the annual amount of precipitation has fluctuated between a minimum of 115 mm (1949) and a maximum of 490 mm (1930). This precipitation is distributed over seven months. As can be seen from the table the year 1973 received the lowest on record in Gao. In Senegal and Mauritania no more than 20 to 30 per cent of the normal rainfall was received during the drought /13/.

Table 2

Rainfall variability in Gao (Mali)
as percentage of 1931-60 mean annual

Year	1966	1967	1968	1969	1970	1971	1972	1973	1966-73
Percentage of 1931-60	71	66	97	71	93	70	62	55	73

The above show that although drought is a recurrent problem in the Sudano-Sahelian zone of West Africa, the drought of 1968-73 culminating in the 1972-73 disaster excels all the previous drought episodes in magnitude and spatial involvement. Annual rainfalls were 50 per cent or more below average, while several places in northern Mali, Chad and Central Niger Republic received only 15 per cent of their normal totals. This phenomenon was not limited to the Saharan fringe; rather it extended southwards to the Guinea Coast. For example, in Nigeria (Figure 5) the 1973 rainfall was 10 to 30 per cent below normal in the south and east parts of the country. In other words the situation was serious in most parts of the country, while it was catastrophic in the extreme north.

It is, of course, natural to ask whether such drastic fluctuations are periodic, quasi-periodic or purely erratic in incidence - and whether any clear trend is visible. Ogallo has recently made a detailed study of the statistics of some 69 rainfall stations distributed unevenly through tropical Africa, and has produced some interesting comments on the variability characteristics /14/. His major conclusions can be summarized as follows:

- (a) The results showed that most annual series indicated some form of oscillation rather than any particular trends;
- (b) Only four out of the 69 stations studied showed a significant increasing rainfall tendency, Casablanca (Morocco); Kasba-Tadla (Morocco), Accra (Ghana) and Luanda (Angola);
- (c) No station showed a general decreasing tendency throughout the study period, which extends from 40 to 109 years;
- (d) Rainfall all over Africa has some real periodic or quasi-periodic effects.

The actual and smoothed curves of rainfall are shown in Figures 6-8. The most important result of Ogallo's work is the existence of cycles of 2.2 to 2.5 years or of 2.7 to 3.3 years. For any given area, especially the arid and semi-arid, larger oscillations of 7, 8 or 10 years may be experienced.

SAINT LOUIS

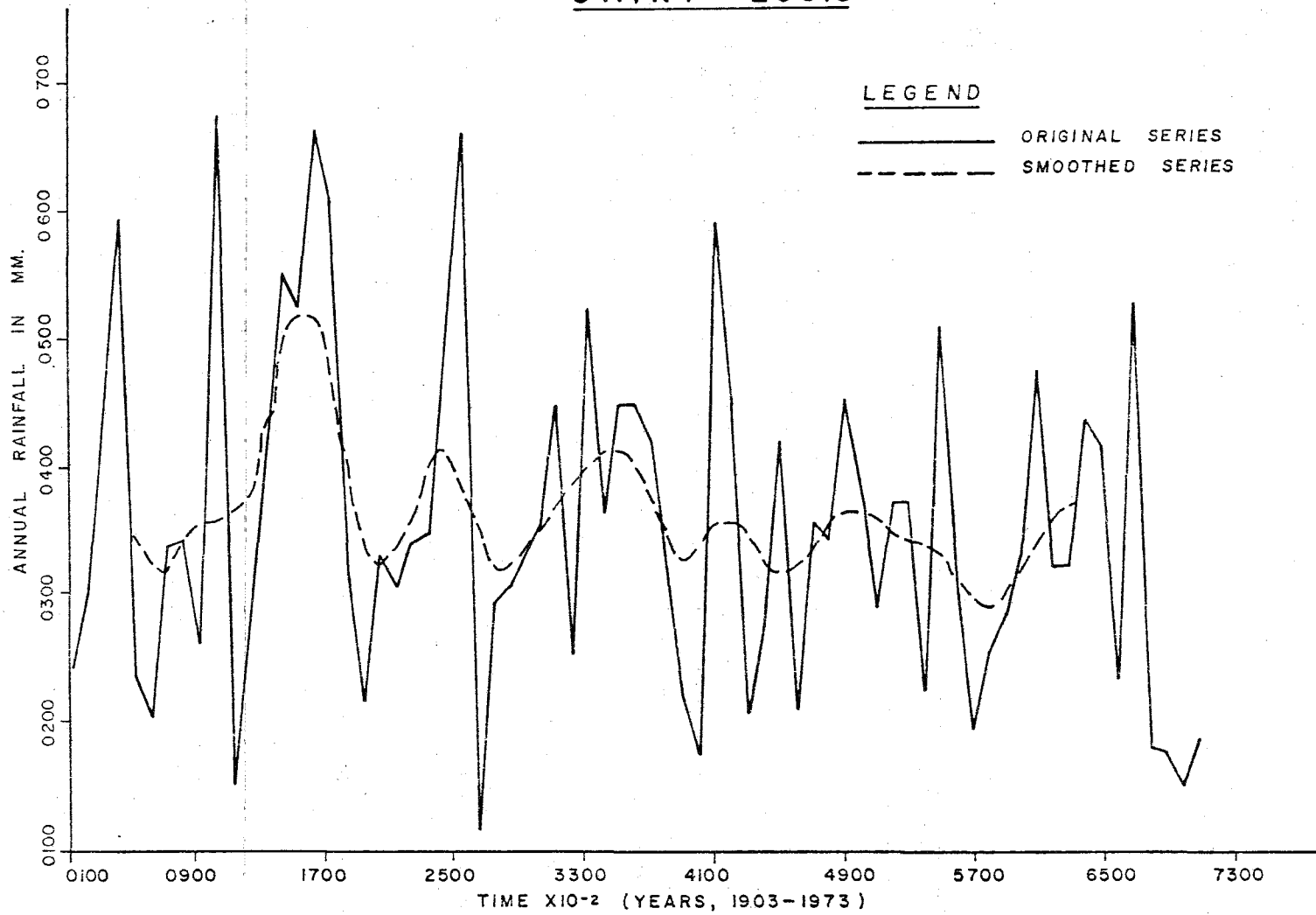


Figure 6 Rainfall characteristics Saint Louis (after Ogallo 14)

LAGOS

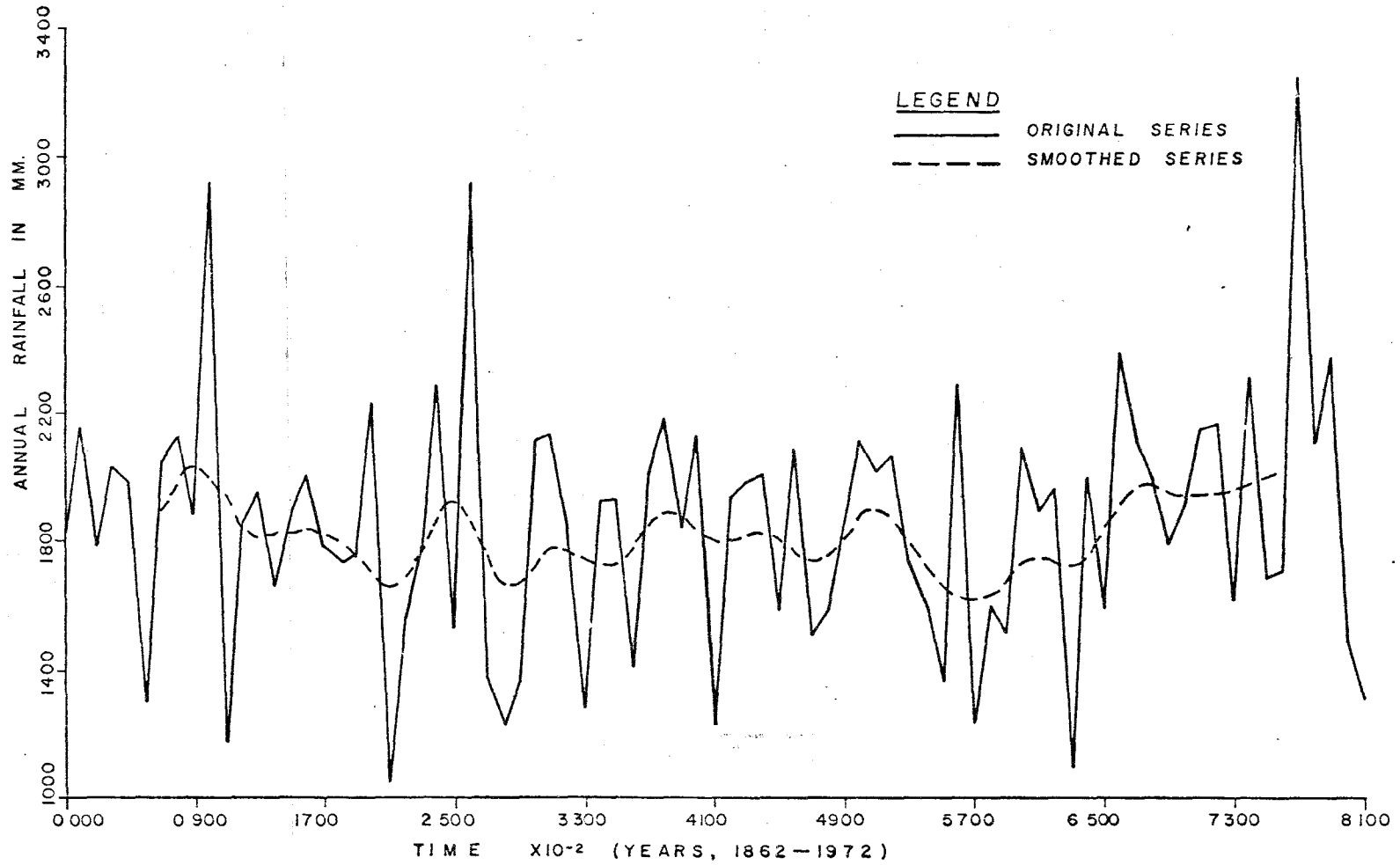


Figure 7 Rainfall characteristics Lagos (after Ogallo 14)

ADDIS ABABA

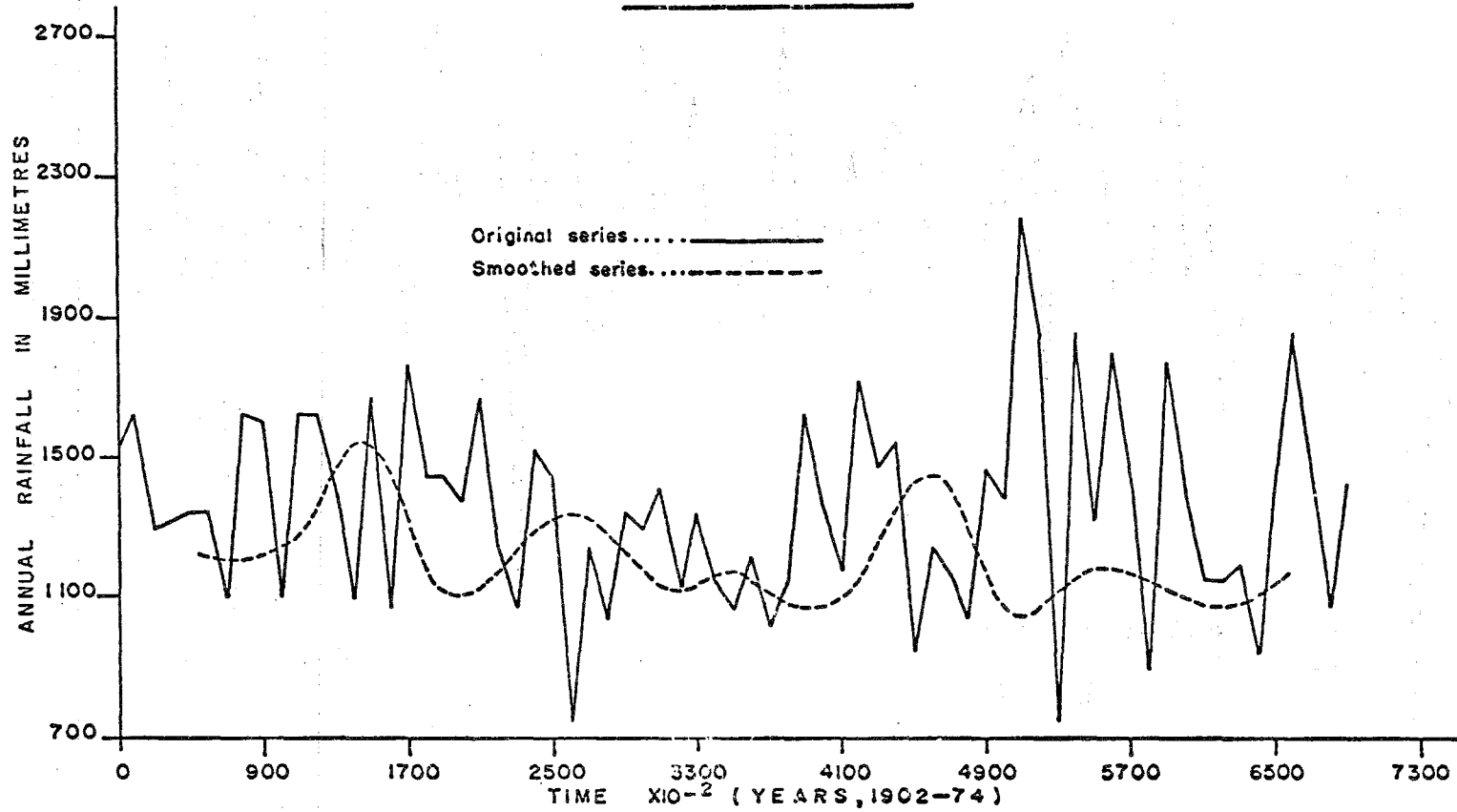


Figure 8 Rainfall characteristics Addis Ababa (after Ogallo 14)

2.2 Land use implications

From this study, and from many others like it, the variability of rainfall is now understood to a certain extent. For example, in some districts of Kenya the agricultural planners know that they can expect a localized rainfall failure every two years, which will bring a localized drought to some districts, especially to the drought-prone areas. They expect a much more widespread drought, which is called a regional drought every four to five years though this is not a regular cycle. The regional type is a common occurrence, and almost an annual event in some parts of the dry areas of Kenya or Tanzania. In the high-potential agricultural districts, a failure of the rains at least once every four years leads to a drought situation that may be expressed in reduced crop yields, rather than in total failure. Finally, perhaps once every decade (with the period varying up to 15 years) there is the equivalent in these countries of a national drought. This is the Sahelian situation, although in Eastern Africa this type is widespread only in Ethiopia, and is much less extensive in Kenya and Tanzania. The last time there was a major drought affecting large parts of Kenya and Tanzania was in 1960 and 1961 and this was not repeated until 1973-1974.

A national drought is potentially disastrous and may lead to total crop failure in many districts, as was the case in West and East Africa during the Sahelo-Ethiopian drought. It may also lead to widespread livestock mortality, because of the progressive destruction of the rangelands as the rainfall gets less and less. It is therefore quite clear that the observed oscillations of rainfall have important land use implications, which may now be summarized very briefly:

- (a) For regions relying on annual crops, seasonal fluctuations in rainfall (within the year) are of greater significance, for they directly lead to crop loss or serious reductions in yields;
- (b) The high frequency of the 2.2 to 2.5 and 2.7 to 3.3 year cycles, as revealed by Ogallo's work, means that agricultural land use in the affected regions should be adapted to the fluctuations, e.g., by using tree crops or by irrigation. In the absence of irrigation frequent crop failures can literally lead to the disappearance of crop agriculture and its replacement by livestock raising; but this is a much more likely response in the more semi-arid margins and certainly in the arid areas. The land use systems in areas that suffer from severe climatic fluctuations have, on the whole, tended to adapt themselves to the expected variations by a judicious mix between crop agriculture and livestock raising, often nomadic livestock keeping, though in some areas legacies of colonialism, or the introduction of cash cropping, have introduced rigidities into this situation;
- (c) In a few cases in East Africa perennial crops like coffee or sisal can fit into the shorter cycles within the observed 2-3 year oscillations, and this fact has for many years been exploited by plantation type agriculture. Where accommodation is not possible, dry farming techniques have been derived in a few countries, where the crops grown or pastures

can make use for one year of the conserved rainfall of the previous two to three years.

- (d) In terms of land use the longer type of oscillations pose a more serious threat because they succeed in disrupting long established systems and lead to the Sahelian type situation. Here one may experience a disaster which calls for more drastic measures. In the case of Kenya, for example, because there were food surpluses in the rest of the country, it was a question of merely distributing famine relief food. In neighbouring Tanzania, though the situation was equally serious, the food imports needed were nowhere near those required for Ethiopia and the rest of Sahelian West Africa.

3. Climatic impacts in West Africa south of the Sahara

With the foregoing background, we shall look more closely at the human adaptation to climatic variability in West Africa. These regions are characterized by highly seasonal and erratic rainfall. Vegetation ranges from scrub to Guinea Savanna. Human activity ranges from pastoral nomadism to seasonal crop cultivation, in which grain crops predominate. Crops are grown mainly under rain-fed conditions, except in the oases and river valley floors (fadama) where irrigation of the dry season crops may be possible. In periods of successive wet years, such as between 1950 and 1967, these activities may extend further into the desert only to be followed by successively drier years in which drought disasters may occur. The significant variations in the climate of the adjacent regions (scrub and savanna), have created a mutual interdependence amongst the adjacent ethnic groups. This will be discussed in the succeeding paragraphs.

Before the advent of colonialism in the Sudano-Sahelian zone, the principal societies of the Sahel - the nomads, e.g., the Tuareg - the farmers, e.g. the Hausa - and the pastoralists, e.g., the Fulani - had developed social, economic, political, and land use systems which enabled their survival within the constraints imposed by the environment of the area [15]. Agricultural activity is restricted by the availability of water and in the southern margins of the Sahelian zone is therefore concentrated along the valleys of the seasonal streams in the dry season, and in the uplands in the wet season. The food production system of the Hausa farmers of the area was based on a complex interaction between social and land management practices. The extended family was the basic unit of the social system, and its head, the mai gida, was responsible for the allocation of labour and for the apportionment of land between cultivated and fallow areas. Crops being cultivated consisted mainly of grains such as millet, guinea corn (sorghum) and some hardy wheat and vegetables. Another function of the head was the distribution of food between that for immediate consumption and that to be stored for use in the dry season, for exchange with the pastoralists for animal products and for long-term storage as an insurance against the possibility of harvest failure due to drought or plagues. The extended family thus provided for the maintenance of land resources via controlled cultivation and regular fallowing, and for the protection of people from the effects of droughts and plagues through controlled use and storage of food.

Fallowing is not the only means of maintaining soil fertility. The area to the north was used by pastoral nomads, the Tuareg and the Fulani, who followed a seasonal migratory pattern which enabled them to take advantage of the grazing resources available in the region. In the dry season these groups maintained their herds in the cultivated area to the south, pasturing their herds on the fallow lands and upon the stubble which remained in the fields after harvest. During this period, agricultural activity was restricted to the areas where water remained available in the fadama (riverine swamps) and thus it was to the advantage of both the farmer and herder to allow animals access to the remaining area: the animals obtained pasture while their droppings brought manure to the soil.

At the end of the dry season both nomadic groups retreated northwards just ahead of the rains and associated pest infestation - grazing their animals on new grasses. They would move north as long as grass was available and then southwards again, grazing the herds on the pasture which had grown behind them as they moved northwards 16.

Both the Tuareg and the Fulani had developed social systems which complemented their economic activity and allowed for minimising the risks that attended drought and disease. The nomadic Tuareg based their economy on animal husbandry and supplemented it with some trade between the northern and southern edges of the Sahara 17.

The animal husbandry allowed the numbers to increase during years of rainfall as an insurance against losses anticipated in years when the rains were insufficient, and pasture became scarce 18. The Tuareg depended heavily upon Hausa agricultural communities for their food supply. Though their animals constituted a major source of food, Hausa farming communities provided their grain in exchange for the protection afforded by the nobles and for animal products. The organization of the Tuareg society reflected the complexity of the economic system and the need to maintain a diversity of activity in order to reduce the effects of drought and disease. Military supremacy over slaves and Hausa was essential to the Tuareg command of grazing in agricultural areas and of the trade routes.

In contrast, the Fulani had developed a more flexible socio-economic system. Mobility was an essential component of their way of life: it enabled them to move their herds from place to place in search of wet season pastures, to avoid disease and to avoid drought-affected areas in search of pasture for their animals 19. Their herd management, like that of the Tuareg, was designed to limit the effects of the drought in that they kept as many animals as possible, and also herded a variety of animals - goats, sheep and cattle.

Ideally, the Fulani aimed at subsisting entirely from their herds, and attempted to control breeding to ensure calving and lactation throughout the year. Numbers were kept as high as possible both because social status was measured by the size of the herd and because a larger herd had a greater potential for survival during a drought.

The emphasis on mobility is reflected in the social organization of the Fulani. The basic unit was the family and, as the southward migration at the end

of the wet season brought many families into areas with restricted grazing resources, they would join in small related family groups and move together around their watering points 20, 21. Before the return of the rains, however, family heads would meet to share information about grazing opportunities for the wet season, to plan their summer itineraries and to set a date for pre-dispersal ceremonies at which marriages, etc., would be celebrated. In the event of drought or disease, the groups would break up into individual family units as each fled to escape disease or to find pasture for their animals.

4. The influence of European colonization

European colonization introduced and imposed a variety of social and economic changes, which enforced modification on the part of the indigenous cultures. Although some of the impact of colonialism was potentially beneficial- educational, veterinary, medical facilities, etc. - the major impact disrupted the symbiotic relationships which had developed between socio-economic groups of the region. Among the measures introduced were the encouragement of the pastoralists to lead sedentary lives and the introduction of the cash crop economy. The expansion of cultivated areas took place at the expense of the more southerly and thus better watered grazing lands; fallow land was reduced; while much of the bushland, which was traditionally part of the pastoralists grazing land, was incorporated into the agricultural area. This reduction in the availability of pasture coincided with an increased demand that resulted from a growth in the animal and human populations of the pastoral societies during the colonial period. The cessation of warfare and the introduction of various welfare services - medical, veterinary and well-drilling programmes - reduced deaths due to raiding, disease and lack of water. These changes occurred in the context of social systems which encouraged large herds and thus rapid animal population expansion was ensured. The result of colonialism has therefore brought to the Sudano-Sahelian zone a modification of the land use system which has changed the traditionally held balance between the farmer on the one hand and the herder on the other. It has also disturbed the mechanisms designed to maintain the productivity of the land and minimize the effects of drought and disease.

5. Ecological disturbance by man; the 1968-73 drought in the Sahel

Deforestation and the burning of the steppes and savannas are types of land use that lead to a diminution of the natural vegetation cover protecting the soil against water and wind erosion. The population of the steppes of Africa use wood daily as fuel. This is the reason for the almost complete disappearance of tree stocks there, so that one gets the wrong impression that the steppes have always been treeless. Le Houérou estimated that daily consumption of wood in this zone at 1 kg per person 22. Even if regeneration is taken into consideration a family of five consumes annually the product from 1 ha of land bearing 500 to 1 000 kg of wood. Since at least 60 million people live in this part of Africa, and are dependent on this kind of fuel supply, the annual damage could be assessed at about 15 million ha 23. In the African savanna, much more wood is wasted than used, partly through lack of caution, causing fires, and partly through the building of huts and enclosures.

Another problem of this area is associated with overgrazing and over-cultivation. This zone as mentioned earlier is characterized by overstocking during a fairly wet period and there is no built-in flexibility to allow for adaptation in case of drought. Overgrazing of the deserts and their margins has taken place in association with the cultivation of the steppes. The driving back of the nomads from parts of the steppes leads to degradation of the sparse vegetation cover in the surrounding semi-deserts on the one hand, and to disturbance of the ecological balance of the cultivated steppes on the other. Serious consequences also result from the ploughing of dry soils in particular. The cultivated top soil is regularly loosened by the plough and is partly cleared of rock debris, which can lead to deflation of huge amounts of fine soil over a short time. In the arid zone of Africa immense masses of fine sediments are transported into the Atlantic Ocean by the trade winds each year. These dust masses were estimated at 6 million tonnes in 1969 24. Satellite photos recorded this dust and sand transport during the drought disaster in the Sahel.

With regard to irrigation agriculture both in the oases and the river valleys of the arid and semi-arid zones salinity of the soil is often a problem; this diminishes productivity. Irrigation has been intensified in these zones in the present century through the construction of dams and deep borings. The extraction of underground water by motor pumps has accelerated the lowering of water tables and the drying out of traditional wells and oases.

The recent Sudano-Sahelian drought invited world wide sympathy; the area affected comprises nearly 5.2 million km² of land which extends from the Atlantic to the Red Sea (Figure 1) and is inhabited by a population of over 60 million people. Historical evidence and oral traditions indicate that Nigeria has experienced severe drought conditions in the past. There were droughts accompanied by famines in the 1890's, 1913-14, 1927, 1934-35 and 1942-48 25, 26 (see also overview paper by Hare). Figure 9 on rainfall trends illustrates the fluctuations since instrument records began.

Figure 9 shows the general pattern of rainfall in the northern fringes of Nigeria (Maiduguri, Kano) and Niger Republic (Zinder) since the early part of the twentieth century. The figure reveals periodic variation but the 1972-73 drought appears to have exceeded all the previous drought episodes in severity and area extent. In 1973 deficits ranged from 10 per cent of the mean in the wettest part to over 50 per cent in the driest north. Kano, for instance, recorded 417 mm which is only 47 per cent of its mean annual total rainfall and the lowest on record. In 1973 the rainfall came late and ended early. In Kano State, for instance where planting normally starts in the last week of May, in that year it was successfully achieved only in the first week of July. The rains ended in some parts as early as August, crops like sorghum and ground nuts being almost entirely destroyed as a result. Many farmers appeared unable to adjust normal cropping strategies in time. Those who appreciated the advantage of planting more of the hardy millet seem to have had insufficient seed to spare for increased planting.

The situation was further aggravated in 1973 when the rains appeared to start early, thus encouraging early planting but then dried up again, correlating with the stagnation of the Intertropical Discontinuity, see Figure 10. In consequence crops already planted and beginning to germinate after early rain were soon killed off

for lack of moisture. Loss of livestock was considerable because the cattle herdsmen who had already retreated northwards in anticipation of the approaching rainy season were caught out when the rains suddenly ceased.

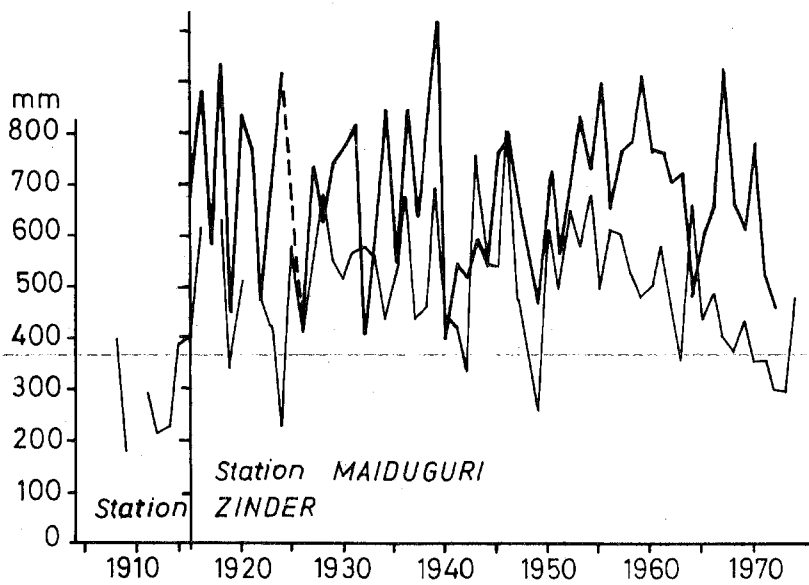
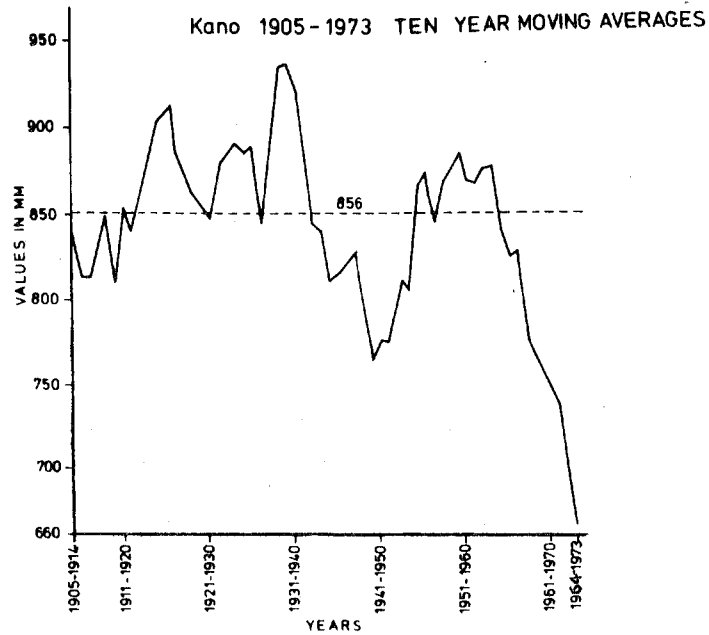


Figure 9. Long term rainfall variability at selected stations

Latitudinal variations of the Intertropical Discontinuity in Nigeria
1969-1973

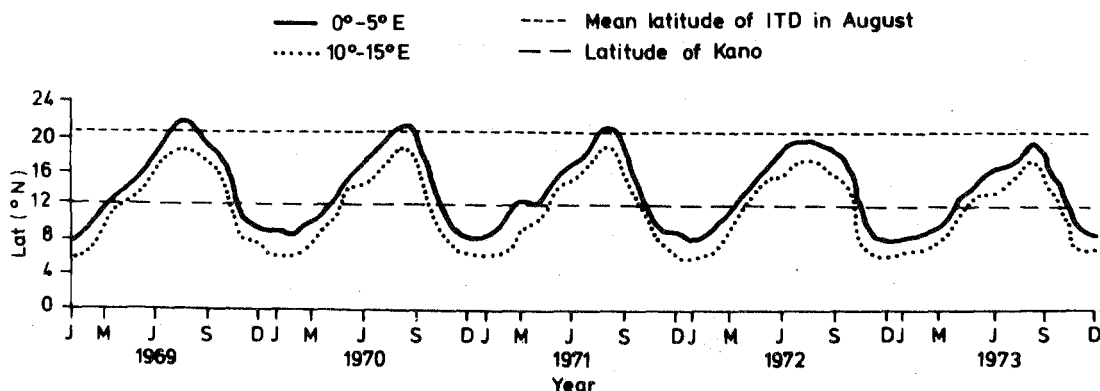


Figure 10. Latitudinal variations of the Intertropical Discontinuity in Nigeria 1969-73

In many drought-affected areas outward migration took place on an extensive scale. Groundnut production was badly affected and export had to be halted. Cattle were being sold off in such numbers that prices slumped. Prices of food stuffs rose on average by 200 - 300 per cent in markets throughout the country over the period 1968-74. The severity of the 1972-74 drought period was so enormous that relief operations had to be mounted on a national scale.

Whereas quite a number of specific observations on the economic impact of the drought are at hand (for example, the loss of the groundnut crop from Kano State in 1973 was put at approximately 115 000 tonnes) a quantitative evaluation is not yet completed. A selection of estimates cited in government documents and reported to newspapers is given in Tables 3, 4 and 5. Further research is being conducted to assess the gravity of this drought period in Nigeria [27]. The results of these exercises show that the drought was a major blow to the Nigerian economy in 1972-74.

Table 3

Estimates of groundnuts graded in the northern states of Nigeria 1968/69-1972/73

Year	Outputs (tons)
1968/69	765 000
1969/70	650 000
1970/71	400 000
1971/72	250 000
1972/73	25 000

Source: Federal Office of Statistics, Lagos.

Table 4

Estimates of Livestock mortality in the Northwestern State 1972/73

Division	Cattle		Sheep & Goats		Horses & Donkeys	
	Population	Mortality	Population	Mortality	Population	Mortality
Sokoto	1 007 100	201 420	3 384 693	676 937	653 041	121 603
Argungu	147 270	29 454	263 769	52 744	46 544	9 111
Gwandu	356 455	71 289	769 588	145 918	163 169	32 581
Total	1 510 825	302 163	4 378 050	875 599	867 854	163 300

Source: Local Administration Estimates

Table 5

Macro-estimates of crop production in Nigeria '000 metric tons

Crop	Source	Average 1961-65	1970	1971	1972	1973	Prelim 1974
Guinea Corn (sorghum)	PYB	4 204	-	3 140	3 561	3 000	-
	MB	4 204	3 500F	3 500F	3 561	3 000	3 300
	US	3 462	4 080	3 140	3 499	2 966	3 500
Millet	PYB	2 615	-	2 688	3 048	2 150F	-F
	MB	2 615	2 800F	2 800	3 048	2 150	2 800
	US	2 825	3 284	2 688	2 584	2 330	3 030
Groundnuts in shell	PYB	1 858	-	1 554	1 763	200F	-
	MB	1 858	900	1 000	1 763	700	1 550
	US	1 419	780	845	1 025	450	700

PYB = FAO Production Year Book, 1973

MB = Monthly Bulletin of Agricultural Economics & Statistics, Vol. 23.
No. 10/11 Oct/Nov. 1974

US = United States Department of Agriculture

F = FAO Estimate

Source: FAO Production Year Book 1973, Table 7.

On a micro-scale the severity of the drought and its impact on land use can be gleaned from the situation in the Bornu State in the extreme north east of Nigeria between 11° and $12^{\circ}30'$ N. This area covers about 57 000 km² of arable land. The human population is about 1 800 000, and livestock about 1 600 000 animal units; the mean annual rainfall ranges between 1 000 and 100mm. The rivers of Bornu province on which the grain crop depended flowed only for a short time or did not flow at all for two seasons 1972/73 and 1973/74. As a result neither wheat nor rice could be grown. Overgrazing is a common feature of this region but it was at its worst in the 1972/73 season. The situation was further aggravated by the influx of herds from other countries. It was observed that after 1971 the rainfall came late and stopped early leaving most crops immature except along streams; crop failure in 1972 ranged between 20 and 60 per cent. Loss in livestock was estimated at about 400 000 including about 30 000 emergency slaughter. This is about 10 - 13 per cent of the total population. The total loss has been estimated to be 20 million Naira (N1 = US \$ 1.60). The average annual production in this area of the main food crops (guinea corn and millet) is about 2 351 000 tons; losses in these crops ranged between 20 per cent and 100 per cent with an average of 50 per cent total loss due to drought, i.e., 1 175 500 tons valued at N82 250 000 28.

A specific case study from the Sahelian parts of the Republic of Niger in West Africa was presented in the summary of case studies for the United Nations Conference on Desertification 29. This was an area approximately 100 000 km² in extent, which is largely arid or semi-arid (rainfall from 100-350 mm per year falling over 2-3 months in the summer and highly variable from year to year and from place to place). The area is largely devoted to pastoralism, with some rain-fed agriculture in the wetter southernmost districts. The whole area supported a total population of 115 000 giving an average of 1.15 persons km⁻². But the livestock population which formed the main support for this human population was much higher. There were 2.0 camels, plus 4.2 head of cattle, 2.3 head of sheep and 5.3 goats for every square kilometre of the area. In the words of the study, these livestock numbers were within the potential carrying capacity of the native pastures, but they were maintained by important seasonal movements. However, important socio-economic changes had occurred in the region before the (Sahelian) drought, accelerated by above average rainfall in the preceding decade. These included:

- (a) A breakdown in control by the Tuareg society over the movements of pastoralists and grazing animals;
- (b) An increase in population (annual growth rates 2-3 per cent), among the pastoral nomads as well as among the cultivators in the south;
- (c) An increase in stock numbers due to the improvement in veterinary services and to the entry of other nomads into the area;
- (d) A northward encroachment by agricultural land use, with related new settlements accompanied by ecosystem damage or destruction. (This land in normal years would be regarded as highly unsuitable for agriculture); and

- (e) The development of deep wells and boreholes equipped with motor pumps, particularly in the sandstone plateau area lacking shallow groundwater.

Then came the Sahelian drought marked by annual rainfalls in each case less than one half of the mean annual figure from 1968 - 1973. This ended in a livestock mortality estimated at 80 per cent or more (especially cattle and sheep). These livestock mortalities were explained in terms of the cumulative effect of drought stress on pastures, and heavy localized grazing pressure encouraged by centralized watering facilities. Here as in other examples already quoted, the collapse of the land use systems was not brought about entirely by rainfall failure, but also by what from hindsight was now obvious: that some of the planning decisions of the last few years had been at fault.

6. The impact of rainfall variability in East Africa

It is clear from the deliberations at the United Nations Conference on Desertification that the greatest blame for the collapse of the land use systems in the face of climatic fluctuations in general and rainfall fluctuation in particular must be laid at the door of man and his destructive ways. To quote one of the component reviews:

It is not easy to disentangle natural from man-made climatic change. A man-made change is physically real, and may be irreversible. Natural systems are self regulating, and hence stable; but they are not always so. They may contain potential instabilities that can be triggered by man's actions 6.

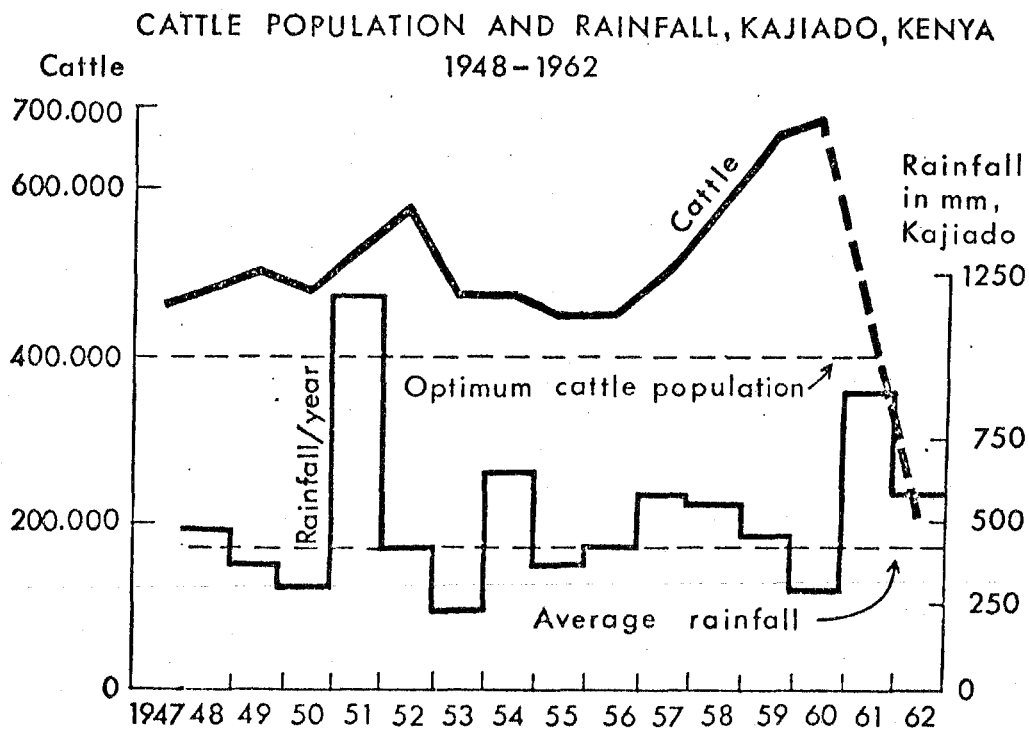
But the same review adds:

Variability in time and space is not without value to man complete climatic stability and predictability, if they existed, might prove harmful both to man and his support systems.

Just as natural ecosystems evolve considerable resilience in the face of high climatic variability, so also should the accompanying land use systems. The problem with many of the agricultural and pastoral systems that have been introduced into the fragile ecosystems is that they do not try to adapt to the given conditions, but rather hasten the process of ecosystem destruction 30.

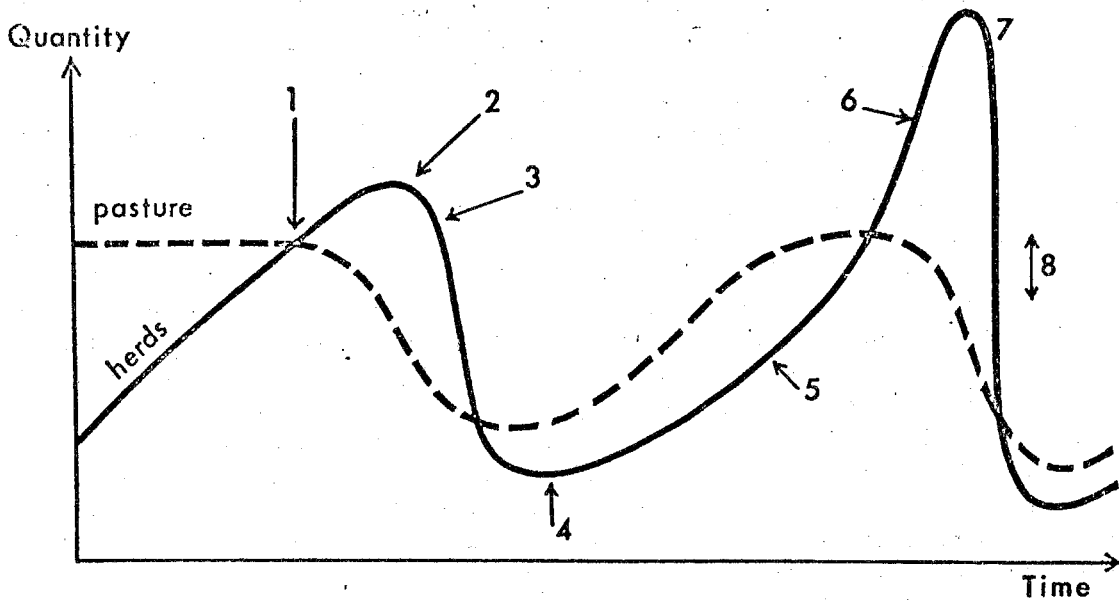
In his summary of recent international meetings on arid lands and rangeland problems, Le Houérou 31 noted that continued rangeland misuse was resulting in such problems as the reduction in plant cover and biomass, an increase in erosion, a reduction in productivity of rangeland (a drop in the carrying capacity of the land), an increase of unpalatable as well as of annual plant species, thinning out and sometimes the disappearance of valuable forage species, and of wildlife which depend on these ecosystems.

The rangelands of Ethiopia, like those of the Sahel, are located in areas receiving less than 600 mm of rainfall a year, and more often below 400 mm of rainfall a year. In good years when the rainfall is plentiful there is a tendency to use even marginal areas with average annual rainfalls between 250 - 500 mm per annum. And for a time the carrying capacity of the land appears to have improved. Livestock numbers kept by the nomadic population increased out of all proportion to carrying capacity (see Figures 11 and 12). To make matters more complicated the agricultural populations move from high potential areas in the highlands down to the plains and medium potential lands during these periods of high rainfall. When the rains begin to swing towards drier conditions for several months or even years, as during the recent drought of the early seventies, there is a forced retreat. In Ethiopia it is not always easy to accommodate such a forced retreat. Between 1972 and 1974 the cultivators fled to the nearest urban areas in search of food, and many who could not find it, particularly in the Wollo district in eastern Ethiopia, perished from the drought [32]. The nomadic pastoralists also made a hasty retreat to the higher as well as wetter ground, leaving in their wake large numbers of dead livestock. The direct effect of drought in Ethiopia led to the destruction of an estimated 80 per cent of the cattle, 50 per cent of the sheep and 30 per cent each of goats and camels [33].



Source: [20]

Figure 11. Diagram of Cattle population and Rainfall, Kajiado, Kenya 1948-1962



(Quoted in Rapp, A., et al, 1977)

Figure 12. Generalized diagram of fluctuations in cattle numbers and pasture after disease control campaign (after J. Swift, 1974)

1. Herds at carrying capacity (c.c.).
2. Animals weakened by food shortage and susceptible to disease.
3. Disease outbreak. High mortality.
4. End of disease. All animals vaccinated to prevent further outbreaks.
5. Herds below c.c., grow quickly.
6. Herds greatly exceeding c.c.
7. Pasture exhaustion. High mortality.
8. Same cycle as before the disease campaign but with wider fluctuations.

In Kenya the dry lands are regarded as a liability to the rest of the country. In any drought of national proportions like that of 1961 and 1962, the country spent at least K£5 000 000 per annum on famine relief and most of this money was spent in the semi-arid areas. The same story was repeated between 1975 and 1976, only this time the drought was less severe and the country was more prepared with famine relief measures, in which surplus districts aided the deficit areas.

The drought-prone Masailand area of Kenya, which is largely occupied by the nomadic pastoralist Masai, often suffers from excessive livestock mortality during drought situations (see Figure 11). The best example from this area was observed between 1952 and 1962. Wet years have abundant grass growth and cattle multiply rapidly. Dry years reduce the growth in grass, and the subsequent deterioration of rangeland causes a marked drop in cattle numbers. The initial growth in numbers, however, also depends on improved veterinary services with vaccination against epizootic diseases like rinderpest and others. During droughts most of the cattle die from starvation, but many also die from disease. Thus droughts bring disaster, not only because of starvation, but also because in good years the cattle numbers had been

allowed to exceed the carrying capacity of the land (Figure 12). Similar conditions occurred in 1975-76 with equally high loss in stock numbers in Masailand despite government efforts to encourage group ranches as a new method of land use and to provide more plentiful water.

In 1974 Swift attempted a generalization of the relationship between carrying capacity of livestock numbers, with special reference to the more susceptible animals, namely cattle 34. All is well when livestock numbers are at or below carrying capacity. Then numbers begin to exceed carrying capacity, and grow until the animals fall prey to disease. The catastrophic drop in livestock numbers that follows is due to disease and range failure in combination. The variation of rainfall, change in range quality, and incidence of disease interact frequently. The lesson to be learned is that in areas of such low rainfall "there is less latitude for errors in land use methods than in areas of better rainfall, and the effects of bad land use are consequently seen quickly and more severely" 35. Uncontrolled pastoralism with stock numbers well in excess of carrying capacity can only lead to disaster during the years of unusually low rainfall.

The destruction of rangeland by unwise land use systems in favourable years is the most serious problem facing planners who are trying to bring about improvements in living conditions in these areas. The same can be said of inefficient systems of subsistence cultivation where migratory cultivators move on to essentially rangeland areas in years of above average rainfall, only to be driven back when the rains fail.

7. Climatic variability and land use in regions of rain-fed cultivation

Much of this paper has dwelt on the impacts of climatic variability on pastoralist and semi-pastoralist areas. Some mention has already been made, however, of the effects of climatic variability on arable cultivation, especially by groups which could be referred to as migratory cultivators. Like their neighbours the pastoralists, they have suffered badly from rainfall fluctuations.

The problems presented by regions on the margin of agricultural land use are different from those of the pastoral or pastoral regions. In the Sahel, Ethiopia, Kenya or Tanzania, these areas are characterized by low cash incomes per family. The ever present danger of malnutrition is there because the land can barely provide the necessities for the population. Attempts to change the situation by modernization in land use through the introduction of cash crops like cotton, groundnuts, etc., have tended to complicate rather than simplify the matter. As we have seen, the widespread introduction of cash crops in West Africa, especially cotton and groundnuts, has been specifically blamed for pushing agricultural land use too far north and into the desert margins. When the rains fail such agriculture is forced to make a hasty and unceremonious retreat.

Modern technology has been brought to bear in helping the various traditional land use systems to adapt to conditions where rainfall fluctuations are a fact of life. These may be summarized briefly as follows:

- (a) Effective control of soil erosion by the use of soil conservation measures;

- (b) The early or even dry planting of crops (which has been encouraged in East Africa for the last twenty years) to make the best use of the rain;
- (c) The use of quick maturing or "Drought escaping" crops like sorghum (Sorghum vulgare), bulrush millet (Pennisetum typhoideum), Teff (Eragrostis Teff) or the new short growing maize varieties, such as have been introduced into the semi-arid areas of Kenya (Katamani Maize) or similar areas in Tanzania (Tabora or Dodoma maize); or the encouragement of legumes like cowpeas (Vigna sinensis), gram, or various types of quick maturing bean varieties;
- (d) The encouragement of affected families to plant famine crops like cassava (Mannihot utilissima) to provide for times of real food shortage;
- (e) The use of animal and artificial fertilizers to accelerate crop growth as well as to increase yields in years of adequate rainfall.

It is normally found that the soils of semi-arid zones are no barrier to agriculture. If anything, they tend to be more fertile than those associated with the forest zones [36]. Most important is the careful selection of the most appropriate crop husbandry or land use system [37]. Only the most ecologically suitable crop varieties will survive the harsh climate and give acceptable yields able to support the human population. During droughts such as those recently reported for Ethiopia, the cultivators who were ill-adjusted to their environment suffered even more severe fates than the pastoralists who did not give up until they had lost over 80 per cent of their livestock. It is easy to blame the cultivators for having extended an unsuitable form of land use to the semi-arid lands. But it is difficult to pass any definite judgement.

In the final analysis, it is not easy to make categorical statements about the effect of climatic variability, and especially about rainfall variability on agricultural land use. Agriculture is the meeting point of various physical, economic, social and even political factors. It is safe to say, however, that several seasons or years of very low rainfall totals result in the decline of crop yields, or the complete disruption of the various agricultural and pastoral land use systems.

3. Summary and conclusion

The foregoing discussions offer a basis for some generalizations on the climate and land use in Africa, especially in the areas marginal to the Sahara Desert, and in the regions of variable rainfall in East Africa. These areas experienced, and will continue to experience, climatic variations. Land use strategies have therefore to be evolved in order to build in checks and balances in response to the climatic variability.

Before the advent of Europeans in West Africa, the adaptation by the natives in different zones - the Hausa as farmers, the Tuareg and Fulani as pastoral nomads - provided a symbiosis which ensured an effective land use management. The

introduction of cash crop economy and other social amenities - educational, veterinary and medical services - has disrupted the original pattern and created pressure on land use. The effects of this pressure are most felt in the marginal areas in the times of crises such as the 1968-73 Sahelian drought. Overpopulation, overgrazing and overcultivation lead to soil erosion, aeolian deflation and desertification. The deduction one can make from this is that in Africa the impact of man on the land's productivity has reached a level comparable with that due to natural climatic fluctuations. We may, moreover, be on the fringe of anthropogenic climatic fluctuations on a global or at least hemispheric scale (Flohn, 1977).

Though the story in East Africa differs in detail from that of West Africa, the basic principle is the same: that the impact of climate arises from climatic variability rather than from a prolonged change towards greater aridity. Here too, however, it is the interaction of ill-advised land-use systems and interventions by modern technology with the periods of drought that create the effects. And here too the possible threat of global anthropogenic climatic fluctuations lingers in the background.

A lack of adequate knowledge of these climatic vagaries on a weekly, seasonal and period basis is the major handicap to effective planning of planting dates, types of crops to plant, given a certain amount of rainfall, and appropriate schedules for pastoral migration - should political circumstances make that possible. Since these areas will continue to be occupied, given their potentialities under normal years, there will be a need to intensify research on the measures that can be taken to ensure that the land use characteristics in these marginal zones conform as much as possible to climatic realities.

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CLIMATIC VARIABILITY AND FORESTRY

A. Baumgartner*

A. GENERAL INFORMATION

1. Principal Aspects

The relationship of forests to climate has two main aspects:

- (a) forests react to fluctuations of climate; and
- (b) Climate reacts to changes of forest cover.

Correspondingly one has to differentiate between:

- (c) the influence of climate at the site on the forest stand or on tree growth; and
- (d) the influence of the specific forest climate on the environment of the forest.

It is of importance in this respect to be aware that trees have a long life. The period from seedling to maturity is, depending on climate, more than the lifetime of one generation of man. Single tree species, like the sequoia or the bristlecone pine, record by their tree-ring width sequence the climate variability of hundreds or thousands of years. Tree growth integrates or compensates climatic fluctuations; however, there are critical phases in the tree life open to serious impacts of extreme meteorological phenomena. Thus the problem of climatic variability in relation to forest has a rather specific note, compared with the other topics discussed at this Conference.

1.1 Tree, forest and wildland, main components of the biosphere

The importance of climate to forest, or of forest to climate and to the biosphere, has to be evaluated on the one hand according to the fraction of the earth's

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surface (or of the continental surface) that is forested, plus their distribution, and on the other hand by the function of forests in the biosphere.

1.1.1 Forest areas and types

A review of the earth's surface cover and its distribution on the globe, as well as the annual net dry matter production and productivity related to unit area, is given in Table 1 after Lieth ^[1], and others. Less than a third of the 510 million square kilometres of the earth's surface is land, of which approximately $120 \times 10^6 \text{ km}^2$ have a plant cover. About $50 \times 10^6 \text{ km}^2$, or 10 per cent of the globe, are covered with forests, including closed forest, or open woodland such as savanna, chaparral or shrubs. It is a question of definition whether to count also shrubby vegetation in semi-arid regions as forests; without them, the forest area is reduced to about $44 \times 10^6 \text{ km}^2$.

Table 1

Earth surface types, their partition, annual net dry matter production and productivity

	<u>Area</u>		<u>Production</u>	
	10^6 km^2	per-cent	per-cent	10^9 ta^{-1} $10^3 \text{ tkm}^{-2}, \text{a}^{-1}$
Globe	510	100		155 0,31
Sea	361	71		55 0,15
Land	149	29	100	100 0,67
Forest	50	10	33	65 1,30
Woodland	7	1	5	4 0,57
Wildland ¹⁾	30	6	21	7 0,25
Grassland	24	5	16	15 0,67
Cultivated	14	3	9	9 0,65
Dry Deserts	9	1	6	. .
Polar	15	3	10	. .

1) Tundra, Steppe, Wet and Water Surfaces

Source ^[1]

As regards land surfaces, which make up $149 \times 10^6 \text{ km}^2$, or 29 per cent of the globe, the forests cover about $50 \times 10^6 \text{ km}^2$, or 33 per cent of the continents. $24 \times 10^6 \text{ km}^2$, or 16 per cent, may be classified as grassland, and $14 \times 10^6 \text{ km}^2$, or 9 per cent, are cultivated. Almost one third of the land areas are less productive or totally unproductive, including the $30 \times 10^6 \text{ km}^2$ (21 per cent) of wildland in the

form of tundra, steppe, bogs and inland surface waters, and the 9×10^6 km² of dry deserts, and 15×10^6 km² of polar and inland ice surfaces.

Table 1 also gives comparative data on the net photosynthetic production of plant matter. The global total is evaluated at 155×10^9 tonnes of dry matter per year. The share of the oceans is 55, and of the land surfaces 100×10^9 tonnes. The ratio of sea to land is hence 1:2. Forests contribute 65×10^9 tonnes, which is 42 per cent of the global total, or 65 per cent of the production on land. Forest is hence the main organic system in the biosphere for the exchange of carbon dioxide and oxygen. On the average it has the highest rate of productivity, measured in tonnes of dry matter per unit area and time. The high productivity of forests is caused by the permanence of the growth-system. It exceeds the productivity of cultivated land 1 to 3 times, of grassland 2 times, and of the oceans up to 10 times. Land use change due to afforestation or deforestation are hence very aggressive anthropogenic actions. Forest-cover and its change should therefore be incorporated as parameters into climate models.

1.1.2 Present world forest distribution

The regional forest distribution is illustrated in Figures 1 and 2 by 5-degree zonal means, expressed in percentages of the total area of the zones. The percentages for the global meridional distribution are:

Latitude	0	10	20	30	40	50	60	70	80°	
North	28,9	7,9	7,4	6,7	10,6	33,8	45,4	4,9		per cent
South	36,8	22,8	6,4	6,1	3,0	0,3	.	.		per cent

Characteristic is the concentration of forests in the humid zones of the tropics, and in temperate latitudes. More details on the type of the forest formations and their contribution to the production are given in Tables 2 and 3. The data, evaluated by BrÜnig [2] and FAO [3,4], are based on statistics for productive or managed forests. The total area is about 4 000 million hectares or less.

Roughly 53 per cent of the world forest area is situated within the tropics, which incorporate 203×10^6 km², or 40 per cent of the globe (71 per cent is sea, 29 per cent land). The 53×10^6 km² of tropical land surface are about 42 per cent covered by forests. They contribute 75 per cent of world forest dry plant matter. With more than 11×10^6 km² and 55 per cent forest cover, South America is the main forest continent. The forest ecosystems of the tropics are very sensitive to climate fluctuations (see Section 7.3).

Nine per cent of the productive forests belong to the warm temperate zone, and 6 per cent to the cool temperate. Thirty-two per cent are Boreal forests, including the Tundra. The temperate forests may compete very well with the tropics as regards productivity, but the total production diminishes towards northern latitudes mainly due to the smaller forest areas, or to unfavourable climatic conditions, as in the Tundra.

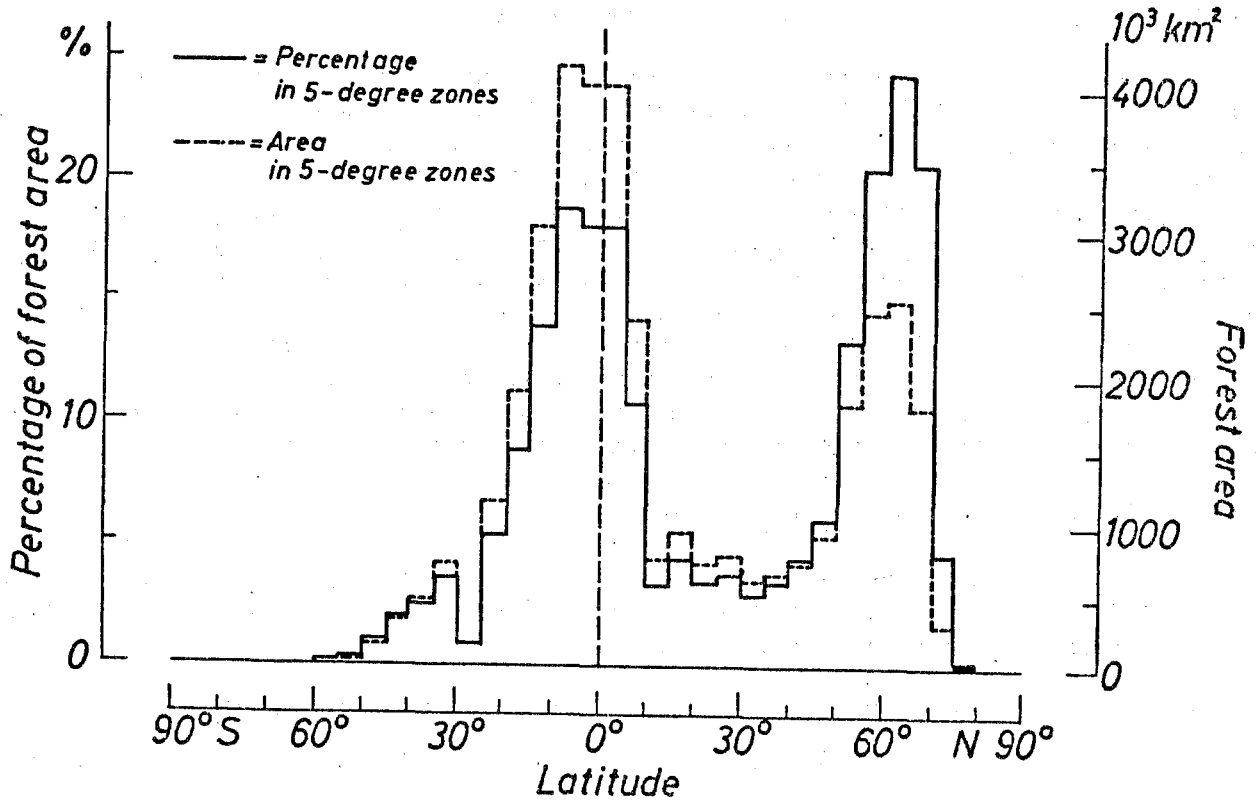


Figure 1 Latitudinal distribution of the forested land area of the earth in 5-degree zones. Percentages related to total zonal areas.

1.2 Forest: productive and protective cover of the earth

Forests have many functions. For man, no doubt the primary role is as a producer of wood; however, there is an increasing awareness of the influences and functions at the site, and on the environment.

1.2.1 Global wood stock and wood production

Wood is a renewable resource. World forest plant matter production is assumed to be 65×10^9 tonnes per annum. The whole stock is about 30 times greater. One kg of wood has a content of 0.5 kg carbon; the carbon stock in the existing forests therefore is about $1\,000 \times 10^9$ tonnes. Seventy per cent of the forests are broadleaved (Angiosperms) and 30 per cent coniferous (Gymnosperms) trees.

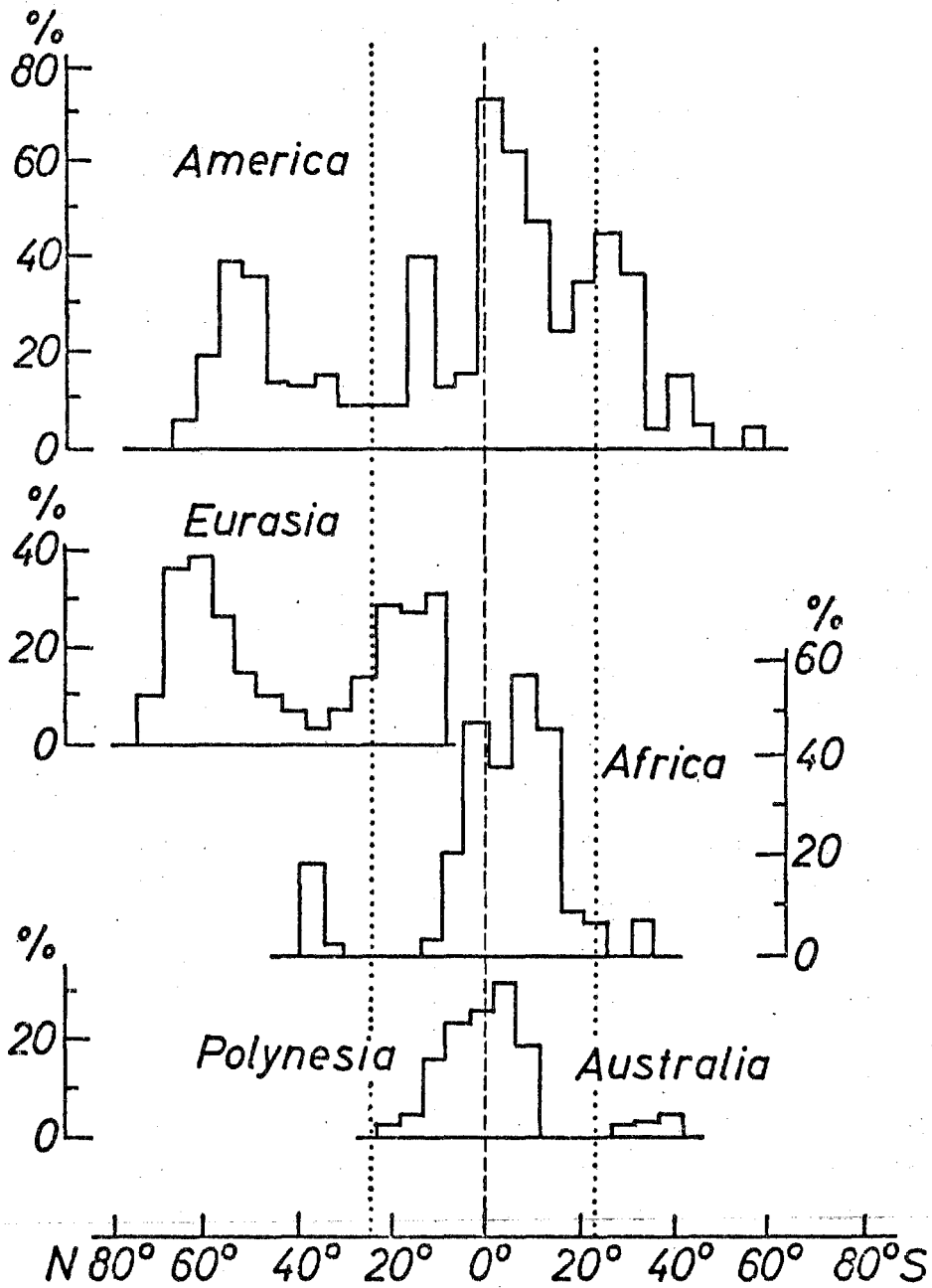


Figure 2. Latitudinal distribution of the forested land area of the continents in 5-degree zones. Percentages related to total area of specific continents.

Table 2

Type of forests, area and net annual above ground dry matter plant production (NAAP).

Formation	<u>Area</u> 10 ⁶ ha	per cent	tha ⁻¹ , a ⁻¹	<u>NAAP</u> 10 ⁶ ta ⁻¹	per cent
Tropical					
Wet-evergreen	550		21	11 550	
Moist-deciduous	750		17	12 750	
Dry-deciduous	700		7	4 900	
Dry-thorn	50		3	150	
Semi-desert	<u>> 100</u>		< 1	.	75
Total	2 150	53		29 350	75
Temperate-warm					
Evergreen mixed	130		29	3 770	
Deciduous mixed	50		6	300	
Sclerophyll	<u>180</u>		5	<u>900</u>	
Total	360	9		4 970	13
Temperate-cool					
Wet evergreen mixed	20		20	400	
Wet deciduous mixed	10		15	150	
Moist deciduous mixed	220		10	2 200	
Dry-Sclerophyll	<u>10</u>		6	<u>60</u>	
Total	260	6		2 810	7
Boreal					
Moist Conifer mixed	600		3	1 800	
Wooded Tundra	<u>> 700</u>		< 1	.	
Total	1 300	32	4	1 800	5
Grand Total	4 070	100		38 930	

Source: 2

Table 3

Productive Forests
Area, average production, use.

	Area 10^6 ha	Woody per cent	Production ¹⁾		Removal 10^6 m^3 a^{-1}	Timber per cent	Fuel per cent
			m^3 ha^{-1} a^{-1}	10^6 m^3 a^{-1}			
Africa	190	6	0,8	150	95	10	90
America, North	631	34	2,3	1450	355	89	11
America, South ²⁾	1130	55	2,7	3050	182	16	84
Asia, Pacific	537	18	2,5	1350	245	48	52
Europe	175	32	2,5	440	279	65	35
USSR	920	43	1,9	1060	299	70	30
Total	3583	35	2,1	7500	1455	59	41

1) Without bark 2) Including Central-America and 400×10^6 ha Savanna or chaparral

Source: 3,4

FAO 3,4 has reported that the annual cut of wood, out of 2.8×10^9 hectares of accessible forest, is around 1.45×10^9 m^3 . The cut has an economic value of approximately US \$50 $\times 10^9$. Fifty-nine per cent of the wood is used as timber, or as pulp for paper and cellulose fibres, etc., and 41 per cent is fuel wood. The quantities of production, removal and use are listed in Table 3 for the continents and for the globe. The demand for wood is rapidly increasing; in Europe it should double by the year 2000. In spite of this, climatic fluctuations, whether by warming, cooling or by moisture changes, will not disturb the world supply of wood. The effects of such fluctuations are present, as tree ring records show, but slow growth in one year or period may be compensated by favourable conditions the next year or period. Decreasing yields in one climate zone of the earth may also be compensated by increased yields in other zones. The market demand can be satisfied also by better management and intervention into unused stocks, as well by imports from surplus areas. Nevertheless, there are other ways in which climate and climatic fluctuation influence forestry and wood production, and the health, vigour and growth of the local stands.

Forest biomass production renews the energy resource of the globe by storing 0.5 to 2.5 per cent of the solar radiation flow over the forested area. The use of wood as fuel, recently 41 per cent of the removal, is based on the energy release of

17-21 kJ per gram of dry matter. The world total of annual energy fixation in the wood biomass is of the order 1.2×10^{18} kJ. White [5] investigated the use of tree plantations for fuel in competition with coal, oil or gas-burning. At the moment the use of land for fuel production cannot compete economically with these other energy sources. It is conceivable, however, that chemicals, yeasts, proteins, sugar, etc. will be future products of wood processing.

1.2.2 Protective role of forests for men, animals, plants and soils, historic monuments, etc.

Forests provide services that improve the quality of life. In hot climates they give shadow and prevent overheating, in cold climates they reduce winter stress. They prevent soils from deflation by wind, erosion or degradation. They conserve historic monuments and give wildlife or secondary flora the ecological environment in which to live and survive. Forests are the most developed and complicated terrestrial ecosystem, with a delicate internal equilibrium, which is closely correlated with external factors, such as climate. The more forests, like plantations, are artificial, or trees are far from their natural ecological environment, as in cities, the stronger are the impacts of climatic fluctuations. The value of forest and trees for such purposes as protection, air purification, recreation, aesthetic appreciation, and hydrologic functions for water flow and quality has proved very difficult to measure and to express in terms comparable to those of wood production [4]. Knowledge of the magnitude of climatic fluctuations is important to give stability to the artificial establishment of a green environment.

2. Specific properties of forests

Forests develop by their structure specific climatic, hydrologic and hygienic properties. They influence energy and water balances and the movement and quality of the atmosphere. Forests respond to climatic fluctuations with a feedback on the climate itself. In short, a description of the peculiarities, of the response functions in the interplay between forest and the climate system, and an assessment of the relative value for climate are given.

2.1 Forests as earth-atmosphere interface

Mature forests incorporate in their stands organic masses of the order of 500 tonnes per hectare, or 700 m^3 wood, which would represent only a homogeneous sheet of 2-5 cm wood above the ground. A further specific argument is the high leaf area index. The leaves of the deciduous forest could cover the earth's surface 10-15 times, and the needles of coniferous forests 15-25 times. The consequence is that the tree surfaces are in very good contact with the air; they absorb and intercept radiation, precipitation, aerosols and the momentum of the air extremely intensively. The aerodynamically rough surface presented to the atmosphere, expressed by roughness parameters of 2-3 metres (see Section 2.4 below), produces high turbulent exchange and mixing rates, which are very active in cleansing polluted air near cities or industries.

2.2 Energy balance, radiation and thermal parameters

The energy exchange in the forests is not concentrated in a thin layer, as it is over surfaces with little or no vegetation cover, because radiation is intercepted and transferred within the stand. Forests therefore do not overheat greatly relative to the ambient air-temperature, and long-wave radiation emission is low. On the other hand there is a high energy income from short wave radiation from sun and sky, due to high absorptivity of 0.9 for conifers and 0.85 for deciduous trees. The net radiation over forests is relatively high as shown in the following comparison with other vegetation surfaces 6:-

	Forests	Crops	Grass	Bare soil	
net radiation, Q	67	53	47	33	Jm^{-2}
potential evaporation	850	760	590	425	mm, a^{-1}

The high energy income will be used by forests in the first case for evapotranspiration. Energetically considered, forests are the most active elements of the land cover.

2.3 Water balance, moisture and hydrological parameters

Forests consume more water than other vegetation, and transfer it by evapotranspiration as water vapour back to the air. The sites of forest stands are characterized by relatively high precipitation. In spite of their own consumption, forested catchments are the most important sources for drinking water, due to the favourable water balance at the sites and to better water quality. The intensive use of water by forests can be evaluated differently in humid or arid climates. This fact can be interpreted in two ways. In arid areas, where water is precious, tree plantations may be luxuries, and they are extremely susceptible to small decreases of precipitation. In humid areas, however, where water is in surplus, trees are welcome to use water, and are relatively stable against changes of water supply. Retention, retardation of run-off, and damping of floods and erosion are other features of forested surfaces, and of high value in the water economy and in dam construction.

The degree of forest cover is of great importance, not only for water, but also for the energy balance of the earth's surface and atmosphere. Moltchanov 7 gave a good example for the impact of forest or wood cover (w) on the run-off ratio (river discharge over precipitation) in the southern USSR:-

Forest or woodland cover (w)	0	10	20	40	60	100	per cent
Run-off ratio(s)	0.42	0.36	0.33	0.26	0.24	0.18	

In the totally forested land only 18 per cent of the precipitation (P) appears as river discharge (D), whereas in open land the fraction is 42 per cent. Changes in forest due to climate are combined with changes in the hydrologic cycle. The influence of climatic fluctuations on forest features such as energy and water balance, and the influence of forests on climate can be related very well by Lettau's climatology equation for annual totals 8:-

$$(1 - D/P) \cdot (1 + H/L) = Q(r.P)^{-1}$$

The hydrological term D/P is combined with the Bowen ratio H/L, where H is the sensible heat and L the latent heat flux; and the Budyko ratio $Q(r.P)^{-1}$, where Q is net radiation and r is the latent heat of vaporization. Deforestation means that the run-off ratio D/P and the return flow of energy to the atmosphere by sensible heat flux will increase; but the flow of latent energy $L=r.E$, with E = evaporation, must decrease. For example, the lysimeter studies at Everswalde, Germany, have shown that annual latent heat flow (L) from bare soil was 17 Jm^{-2} , from short grass 28, from pines 35 and from grass with a high ground-water table, 41. The exchanges of energy and water at the earth's surface are hence very sensitively correlated with changes in forest cover.

2.4 Dynamic properties of forests

The forest crown is one of the roughest earth-atmosphere interfaces. The crown brakes the movement of air, and absorbs the momentum. The dynamic property is best expressed by the roughness-parameter, z_0 , used in the mathematical representation of the vertical wind profile. A comparison of the values for various surfaces is given below:-

	Water	Sand	Short grass	Crops	Forest	City	
z_0	0.01	0.2	1-5	10	300	400	cm.

As regards roughness, a forest is comparable in effect with the house or roof irregularities of cities. The surface drag, energy dissipation and turbulent exchange of air are proportional to the roughness. World maps by Baumgartner and simulations of coverage by Kirchner show a considerable influence of forest on the above terms, and on the angle of deviation of geostrophic wind from the isobar. This implies also an effect on the development of the pressure field and on the circulation of the atmosphere 9,10.

2.5 Forests as source or sink of energy, matter, aerosol and gas

Plant biomass production is based on photosynthesis, where carbon dioxide from air is fixed with water by the energy of short wave radiation. The fixation energy for 1 g CO_2 is 10.7 kJ and for 1 g Carbon is 39 kJ, corresponding to the ratio $\text{CO}_2/\text{C} = 44/12$ of the molecular weights; of the total solar energy flux on the globe of $2.150 \times 10^{21} \text{ J a}^{-1}$, $2.880 \times 10^{18} \text{ J a}^{-1}$ are fixed in plant matter. From 71 per cent of the surface of the globe, the oceans contribute $1.090 \times 10^{18} \text{ J a}^{-1}$. On only 9 per cent of the globe, however, the forests contribute $1.200 \times 10^{13} \text{ J a}^{-1}$. The global average efficiency of solar radiation for plant production is 0.13 per cent. For the oceans it is 0.07 per cent and for land ecosystems 0.3 per cent; but the net effect of individual stands can be up to 2.5 per cent 11. The energy needed to produce a unit of dry matter differs; in general, broadleaved deciduous trees require 17 kJ g^{-1} , which is more efficient than conifers, with 20.5 kJ g^{-1} .

Forests are sources and sinks of carbon dioxide and oxygen for the atmosphere, with periodic cycles and aperiodic rhythms. For the formation of a mass unit of plant dry matter (DM) 1.83 mass units of CO_2 have to be provided and 1.32 mass units of O_2 are released. If, for example, the annual production is $10 \text{ t DM ha}^{-1}\text{a}^{-1}$, then $18.3 \text{ t CO}_2\text{ha}^{-1}\text{a}^{-1}$ are assimilated and $13.2 \text{ t O}_2 \text{ ha}^{-1}\text{a}^{-1}$ are respired. An inverse process is metabolism (see Figure 3). The decomposition of primary plant matter in

soil (roots, stumps, etc.) and of secondary organic matter as litter is a function of temperature, a source of CO₂ and a sink of oxygen. It is an open problem to what extent CO₂-in-and-output are in equilibrium or unbalanced. It is more probable that CO₂- Balance of the forest ecosystem is very sensitive to climate fluctuations.

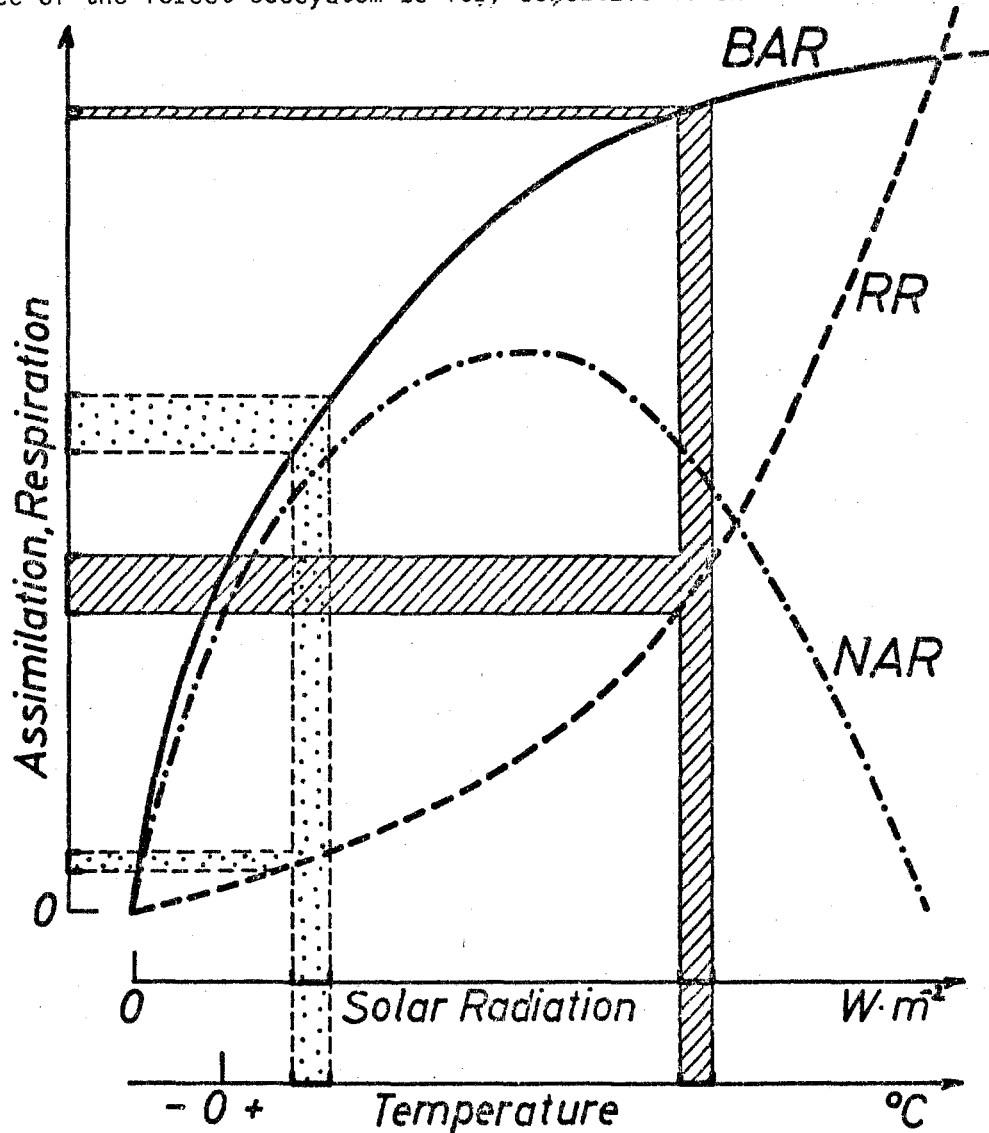


Figure 3: Gross photosyntheses (BAR) related to solar radiation, respiration rate (RR) related to temperature and resulting net assimilation rate (NAR). Pointed or dashed lines give the effects for unit radiation or temperature changes in cool or hot climates.

Not unimportant for atmospheric processes is also the release of terpenes, which are hydrocarbons, and pollens. Forests have a high hygienic efficiency merely by their presence, through the lack of anthropogenic emissions of sulphur, fluorine etc., in their areas. For certain trace gases forest areas are passive sinks.

2.6 Forests and global carbon dioxide or oxygen balance

Forests are very efficient in the global CO₂ balance. From the 285 x 10⁹ t CO₂ assimilated by vegetation annually, 118 x 10⁹ t/a or 42 per cent are used by forests. Compared with the total of CO₂ in the atmosphere, 3 x 10¹² t, the ratio of exchange by forests to storage in the atmosphere is 4 x 10⁻². The atmospheric CO₂ storage would be depleted totally by forest production within 26 years if no return from respiration existed. In virgin forest there may be an equilibrium between assimilated and respired carbon dioxide; in managed forests this is not the case. It is assumed that the annual withdrawal of carbon dioxide from the atmosphere due to the harvest of the stands, before reaching the state of a full succession and to the removal of the wood is of the magnitude 7.5 x 10⁹ tonnes CO₂. There is considerable uncertainty on the buffering potential of CO₂ in wood mass above and organic materials below ground.

The total expired oxygen of forests is 85 x 10⁹ t a⁻¹. By comparison with stored oxygen in the atmosphere, which is 1.3 x 10¹⁵ t, this is very small. The O₂ storage of the atmosphere is in principle untouched by forest processes.

The progressive deforestation in tropical zones may rapidly influence the carbon and nitrogen content of atmosphere. The tropical forests of about 20 million km² with a growing stock of about 10¹² t of dry biomass above ground, are being destroyed at an annual rate of 0.3 million km². If at least one third of the dry matter is burnt or decomposed, about 4 x 10¹¹ t O₂ will be used (= 0.03 per cent of oxygen storage in the atmosphere) and about 5.0 x 10¹¹ t CO₂, or one fifth of the atmospheric CO₂-storage, will be released into the atmosphere. Part will be fixed again by replacement vegetation. Higher carbon dioxide content increases photosynthetic production and yields. Relatively unknown at the moment are the quantities of the CO₂ released by the mineralisation of the uncovered and unshaded soils.

The net effect of global forest cover for the atmospheric carbon dioxide balance is a release of about 10 x 10⁹ tonnes CO₂ per year. This is approximately the same order of magnitude as the anthropogenic release of CO₂ from burning fossil fuels. Hence, land use by forestry is a most important factor, with interactions on the development of carbon dioxide content in the atmosphere and on the global climate.

3. Sensitivity of tree growth to meteorological factors

The vulnerability of forests to changes in climate or to extreme weather events in the scenario of climatic fluctuations must be examined separately for different phases of the individual tree's life. The requirements for undisturbed growth are well-known. Trees may adapt themselves to new conditions and structure of stands or sociology of species will be adjusted. The sensitivity can be observed on this phenomenon. Critical phases under the limits of minimum conditions are the causes of selections, yield reductions, or loss of stands.

3.1 Seeds and natural reproduction

Flowering and fruiting of trees differ from year to year. In the semi-arid zone

flowering is correlated with zenithal rain. Natural seed is missed some years, and then in a single year there will be a fantastic surplus, an apparent natural waste. The germination and production of seedlings, however, depend often on chance events in growing conditions during the vegetative period, for instance late frost, droughts and insect attacks, wet periods and fungus invasion. Especially at the marginal borders of existence, in polar latitudes, alpine altitudes or arid regions regeneration is a climatic problem.

3.2 Plantation

The establishment of artificial forests in the form of plantations is part of a long-term strategy in forestry. It involves climatic risks of many kinds. Mechanized cultivation, and so-called exotic or fast growing trees from foreign climates, are very sensitive to climatic variability, as are monocultures generally. If, for example, tree species, management and silvicultural techniques are based on growth conditions of favourable climates the plantation may fail. Mikola attributed failures of expansion of forestry into the marginal subpolar latitudes to climatic deterioration [12].

3.3 Tree growth, wood quality and yields

Height and volume of a mature tree at the time of harvest are products of climatic influences over a long series of years. Tree ring width, wood density and physical wood parameters are closely correlated with climate [13]. This is true also for wood-quality characteristics, such as branch numbers, inclusions, shape of stem cross-sections, etc. Climatological fluctuations are also an important economic factor for wood industry and technology.

3.4 Sociology and structure of stands

The vertical and horizontal composition of a tree community depends on natural reproduction, on competition, on abiotic and biotic selection, and on pruning and other management of stands. The diversity of tree species and the stability of a forest biome are determined by atmospheric conditions, and are in dynamic equilibrium. Thus what happens in natural succession within the climatic gradient, may occur also through climatic fluctuations at given sites. An example is the behaviour of the fir (*Abies alba*) which in middle Europe is in a marginal situation, and has been disappearing in the last two decades as a result of an unfavourable climate.

3.5 Disease and insect calamities

The development of pests, mainly by pathogens and insect calamities, depends primarily on the thermal and moisture environment, and on the atmospheric transport of germs and insects. There are multi-annual cycles in the development of a pest or in the population dynamics of insects, through distinct climatic successions. The population dynamics of insects can be causally related to climatic fluctuations [14]. Serious outbreaks of insect attacks result in the consumption of foliage and reduction of wood increment, especially in evergreen tree species. Through repeated attacks the tree may be killed. The weather related diseases of fungal, bacterial or virus origin like rust or blight are primary or secondary causes of large scale mortality of specific tree species, such as elm in the last few decades.

3.6 Abiotic hazards in forestry

There are many types of abiotic risks in forestry, which are governed by climatic conditions. Heat or frost, gusty winds, drought and wetness, lightning, fires, hail, snow, avalanches, ice and floods threaten the forests in the different climatic zones and periods in various ways and frequencies. The problem has ecological, economical, and social aspects.

3.7 Environmental influences by polluted air

Anthropogenic constituents of air like sulphur and fluorine injure plant tissues and suppress assimilation and plant production. Acid precipitation influences the soil and fresh-water acidity. The minerals in rain or snow water act as fertilizers, and may increase the forest yields. The importance of these effects, however, has not been sufficiently quantified and investigated in relation to climate.

B. INTERACTIONS

Forestry projects and operations interfere with climate. Forest establishment, management and infrastructure development are normally based on the assumption that existing climate will persist.

4. Forestry planning

Forestry planning has an unusual time scale, compared with political and economic planning. The scale comprises one tree-life and more, which in the sub-polar zone is 150-200 years, in the temperate zone 100 years, and in plantations of the warm humid zone about 30 years. Noble trees, like oak, teak, fir, or tropical hardwoods, need hundreds of years. New plantations are projected on the basis of present climate. Changes of environmental factors during coming growth-periods cannot be corrected without economic consequences. Wet periods in arid regions may favour tree growth for fuel or windbreaks, but in dry periods the plants will dry up. Exotic species, which are planted in temperate zones in a mild period, will die in a period with severe winters, or with droughts, etc. The disappearance of walnut and elm in North America and of silver fir in Western Europe have to be seen under these circumstances.

4.1 Forest establishment and management

The establishment of man-made forest under the premise of continuity of long-term optimal growth is risky in relation to climate, as only probabilities can be considered for the decisions. Site typing, selection of seeds and tree species, silvicultural treatments such as thinning or pruning, are future-orientated, and success is correlated with the subsequent development of climate. The external climate governs the microclimate and the initiated growth processes. Imponderables depending on future climatic influences exist also for harvest and for reforestation. Examples are the fixing of maturity age, the choice of selective cutting or clear cutting, the direction of cutting lines, natural regeneration or plantation, the row distance of plants, individual vitality of the species in the community under external conditions, etc.

4.2 Forest protection

The protection of forests against biotic or abiotic hazards cannot be effective unless attention is paid to climatic facts and trends. Calculations on a meteorological basis for the prognosis of diseases or insect attacks give a good chance of opposing the outbreak of pests in the initial phase, which is better done by natural means than by pesticides. Forest fires and the extent of wasted areas are closely related with climatic fluctuations. Vines 15 connected Canadian and Australian forest fire cycles with the sunspot-cycles. Fire years are coupled with droughts. Snow, ice and storms are further deterrents to wood production in the most important forest areas. BrÜnig classified the properties of trees and stands to avoid risks and losses 16. Knowledge of the probability of abiotic interferences, however, would be of first importance in regard to management activities, and of high economic value.

4.3 Environmental protection by forests

Trees and forest are welcome neighbours in a human settlement, but perform varying functions in the different climatic zones. They are part of the urban infrastructure to reduce overheating, dust and noise and are esteemed for aesthetic and recreational purposes. Trees and bushes are needed to give shade for man and animal, food and ecological niches for wildlife and to extend life into extreme climatic zones, such as semi-deserts. In such environments trees are endangered by the small deviations from normal climate which cause desertification. In high mountains, trees act in the sub-alpine zone to prevent avalanche development and on the slopes and in the valley to protect settlements. The environment aspects of forest as a natural resource are climate-dependent and of such importance that the UN Conference on the Human Environment, Stockholm 1972, considered an F.A.O. proposal for an international research programme on forest influences 17.

C. IMPACTS

Forests have varying annual growth rates and, as a whole, are in quasi-equilibrium with the elements of the environment.

5. Effects of climatic changes or fluctuations

Areal, structural or plant sociological changes, species selection or habit, and growth and yield variations may all be expressions of climatic impact.

5.1 Forest development since the last glacial epoch

Dendrochronology, C¹⁴ - analysis of wood, and pollen analysis tell us the magnitude of impacts by climatic trends on areal forest distribution, on the growth of trees, and on the evolution of species since the last glacial epoch. There are steady successions to so-called climax vegetation, regional movements and retreats of distinct types of forest, and of the forest areas themselves. Small, nearly undetectable but permanent climatic trends have greatest effects on the treelines in horizontal and vertical directions.

5.2 Influence on the productivity in different climatic zones

Correlation analysis permits us to analyse possible impacts of climate on production. There is a strong dependence of productivity on meteorological parameters. An example is the CVP-index of Patterson [18] which shows that the potential wood production by volume is related to the temperature of warmest month, annual precipitation, length of vegetation period, the annual temperature range and the evapotranspiration.

Another example is provided by the set of regressions by Lieth [17], which relate the yield to annual average precipitation, to temperature and to the actual evapotranspiration. It is clear that changes in any of the main bioclimatic elements would have considerable effects on yields.

Climatic fluctuations may have significance in specific parts of the world or globally. Global cooling or warming have different effects in cold and warm climates. Figure 3 shows why this is so. In cold climates a warming raises gross production rate (BAR) considerably and the effect on respiration rate (RR) is smaller; therefore net production increases. In hot climates, however, BAR is relatively independent of temperature change, but respiration and CO₂ outputs increase, and production decreases. Cooling gives inverse effects. Decreases in radiation, or more cloudiness, help deciduous trees to compete more easily against conifers.

5.3 Forests and climatic classification

Climatic types can be classified by single climatic parameters, by combination of meteorological elements, or by the effects of climate. The well-known Köppen-Geiger classification [19] uses an inverse method; it defines the climatic parameters for existing vegetation types, and to a first approximation for forest ecosystems or tree species. This is a first-order definition, and is independent of climatic trends if one assumes that a pine forest, a palm tree or a mist rain-forest demand a fixed bioclimate. If climatic trends alter conditions then the forest can adapt to the new environment, change its area of distribution, or die and disappear. Monitoring of areal distribution and structure of forests by continuous mapping, or by remote geobotanic surveys, is needed. Protected areas, normals of land use and phenological gardens should be, in the sense of benchmark plots, helpful means of evaluating impacts of climatic fluctuations.

6. Impacts of climatic fluctuations on forest at endangered limits

~~Impacts of climatic fluctuations on individual trees or stands are possible~~ in all forest regions, but are most impressive at the spatial limits of specific tree species or of stands at sites with high risk like the sub-polar zone, the alpine tree line (montane) and forests in zones with extreme arid, humid or hot climates.

6.1 Trees at the spatial limits

As has been mentioned in Section 5.3, the existence of specific tree species or stand types is governed and limited by climate. A small shift of minimum values, or continued extreme events such as droughts or severe winters and hard frosts, or mild and wet summers, may start the retreat or extension of the distribution of

individual tree species over large areas. Seed and seedlings are most affected, and mature trees are objects of disease if minimum conditions are not reached. The relatively mild climate in the temperate zone during the last century favoured the cultivation of fast-growing exotic trees in plantations far outside their original homes. Forestry therefore is interested to know the trends of **future** climate in order to avoid errors in investment.

6.2 Forest at borders of high risk

Borders of high risk for trees are the arctic tree-line of the Boreal forest, and the upper timber line in the mountains (the alpine or montane tree-lines). In northern latitudes, with long winters and a short vegetative period, tree growth in height and volume is small. Natural regeneration occurs only in favourable years and plantations are endangered by sequences of strong winters and short unfavourable summers. Climatic fluctuations govern the existence of forest cover. The average altitude of the upper timber line on mountains is a function of latitude. In the tropics, the tree-line may rise to 5 000 m above sea level, as in the Himalayas and the Andes. In sub-polar regions it comes down to sea level near glaciers. Climatic fluctuations may raise and lower the timber line. Of specific concern is the effect of cooling and the depression of the timber line, with consequent loss of soil protection, increase of erosion, land slides on mountain slopes, increase of avalanches, boulders and floods in wild mountain streams.

6.3 Forests in extreme zones

Zones are extreme for tree growth if water deficiency, water surplus, excess heat, drifting sand, etc., prevent tree growth or regeneration. In the sub-tropical arid belts forestry is in first line very risky, due to insufficient water supply. Trees are small, and under harshest conditions there is a transition of closed forest to open woodland, savannah, scrub or thorn-scrub. Plantation in the sub-tropics, with the primary purpose of covering the land with trees for erosion control or for fuel and fibre, is very problematic due to the marginal state of existence and to the uncertainty of future climatic trends. In hot, dry zones new plantations have to be protected by shading and irrigation, but extreme hot and dry periods can destroy the stand in a short time. Forestry in extreme zones needs, more than elsewhere, information on the extent of climatic fluctuations.

D. FEEDBACK

7. Feedback of forest operations with climate

The specific properties of forests explain that any forest operation, whether conservative management or destructive exploitation, has feedbacks with the climate at the site. Depending on the scale of operations, these feedbacks may also be regional or possibly global.

7.1 Forest influences in relation to forest management

Conservative management of man-made or virgin forests does not disturb the functions of forests at the site. Thinning, pruning or careful harvesting alter

radiation and precipitation interception, momentum of air, evapotranspiration, the run-off, and the Bowen and Budyko ratios. Net radiation sensible and latent heat flows decrease; vertical temperature gradients and soil heat flux increase. In the hydrologic cycle, run-off ratio, retention and unit hydrograph, i.e., response of the drainage basin to a specific addition of storm rainfall, are affected. Since normally only parts of the forested area are under operation, and reforestation is practised, no real feedback can be observed.

7.2 Destructive forest operation

Clearcutting is the most effective change in land use for local, regional and global climate. In the course of history, mankind has reduced the forest areas on the globe, mainly in temperate and also in sub-tropical latitudes; but at present, forest clearance is being accelerated mainly in the tropical zone. With the conversion of forests to cultivated land, or with soil erosion on land left waste, the energy, water and biogeochemical cycles are changed. Table 4 reviews the magnitudes of energy balance quantities for various types of land use and cover. The trend from closed forest cover to bare soil is accompanied by decreases of net radiation and latent heat flux and by increases of albedo and sensible heat flux. Flohn has stated that 4 to 5 thousand years ago Central Europe was covered 90 per cent with forests, which now cover about 30 per cent [20]. The conversion to cultivated land reduced net radiation by 12 per cent, and evapotranspiration by 23 per cent, but heating of air rose by 21 per cent. The lower evaporation increased run-off and the Bowen ratio increased from 0.36 to 0.57. The ratio of sensible to latent heat flux H/L (the Bowen ratio) is very sensitive to land use. The connexion between the energy and water cycles means that removing the forest cover and exposing the soil leads to greater dryness and an increased convective heat transfer to the atmosphere. More heat at the surface amplifies the system, more water damps it. Baumgartner [21] estimated that the greatest effects of deforestation on the hydrologic cycle is possible in the tropics at about 5°N, and in the temperate zone at 50°N.

Table 4

Energy balance for different earth surfaces. Frame values

	Q	H	L	E _p	a	H/L
		W, m ⁻²		mm	per cent	
Trop. Rain Forest	110	25	85	1400	10	0,3
Coniferous-Forest	80	25	55	1000	10	0,5
Deciduous-Forest	65	20	45	900	15	0,4
Openland, moist	70	25	55	1000	20	0,4
Grassland	65	20	45	750	20	0,4
Savanna	65	25	40	800	25	0,6
Cropland	60	25	35	300	25	0,7
Bare sand	45	25	20	600	30	1,0
Urban area	45	30	15	600	30	2,0
Semi-desert	45	35	10	600	30	3,5
Dry-desert	70	65	5	1000	35	8,0

Q net radiation, H sensible heat, L latent heat, E_p=0/r potential evaporation, a albedo

7.3 Tropical forests; vulnerability and effects of exploitation

Tropical forests include in the humid zone moist forests at low and medium altitudes and the rain forests with multi-storey structure and closed canopies, the savanna-mosaic, and also xeromorphic woodlands, scrubs and semi-desert thornbushes in the transition to arid climates.

In the huge forests still unexploited, 30 to 50 million hectares of forest land are cleared annually for shifting cultivation and settled agriculture, mostly with the use of fire. Economic and population pressure are rapidly accelerating the deforestation and conversion to agricultural land. In the next 20-30 years all primary tropical forests on easily accessible terrain will be used. The exploitation will affect meteorological and edaphic processes on about $1.2 - 1.5 \times 10^9$ ha of tropical land. The significance of tropical forests for the biosphere has been described by Baumgartner [22]. Table 5 quantifies the meridional distribution of energy and water balance terms. Net radiation is more or less invariant, but latent heat flow increases towards the equator and simultaneously decreases the flow of sensible heat of air. The hydrologic balance is characterized by a sharp gradient of precipitation, evaporation and discharge toward the meteorological equator, [23].

Table 5

Meridional distribution within the tropics of energy and water balance terms.

Energy Balance											
Latitude	North			South							
	25°	15°	5°	5°	15°	25°					
Q	92	94	96	96	97	93	W, m ⁻²				
H	64	46	12	5	28	56	W, m ⁻²				
L	28	48	84	91	69	37	W, m ⁻²				
L/Q	31	51	88	94	71	40	per cent				
H/L	229	96	14	6	40	150	per cent				

Water Balance												
Latitude	North						South					
	25°	20°	15°	10°	5°	0°	5°	10°	15°	20°	25°	
P	62	67	102	148	196	209	182	143	94	60		cm
E	39	45	79	104	112	121	112	100	78	52		cm
D	23	22	23	44	84	88	70	43	16	8		cm
E/P	63	67	77	70	57	58	62	70	83	87		per cent
D/P	37	33	23	30	43	42	38	30	17	13		per cent

Q net radiation, H sensible heat, L latent heat
P Precipitation, E Evaporation, D Discharge

Source: [23]

Characteristic of the tropical moist forest is the extremely heterogeneous composition of tree growth. Several storeys are normally found. Mineral cycles are fast. Ten to 15 t DM of litter per ha are decomposed within months, and at the latest in 1-2 years. On 20×10^6 km² the potential of carbon dioxide release from the soil is of the order $4 - 5 \times 10^{10}$ tonnes CO₂a⁻¹. High precipitation and temperature are very evenly distributed over the year. The ecosystem is very vulnerable and sensitive to levels of precipitation and to its seasonal distribution. Any changes in the seasonality, and in the reliability of rain events, have impacts on the floristic and architectural structure of the stand. BrÜnig stated that complex systems can be more fragile than more simple ones and may be less able to withstand or recover from disturbance [24]. The forest system oscillates narrowly about an equilibrium state, but exhibits a relatively high fragility to interference by man and to severe large-scale perturbation. The trees, mainly the dominants, are, however, adapted in a number of ways against occasional drought periods [25]. The forest is a climax vegetation, maintaining self-made conditions, mitigating the vulnerability of its soils and moderating the influence of intense rainfall on soil erosion and leaching of nutrients, as well as the discharge of the catchment areas. Soil discharge in forested areas is 0 - 100 t ha⁻¹a⁻¹, whereas, in deforested areas it is of the order of 500 - 1 000 t ha⁻¹a⁻¹.

The tropical forests in seasonal climates are structurally more simple and more robust to the environmental impacts of stronger and more effective climatic fluctuations. Adaptation to climate shifts from leaf, tree and canopy xeromorphism to the deciduous habit, beginning in the more exposed tree-top canopy species. This alters the stand dynamics with respect to differential growth rhythms and regeneration. Again this is of the greatest silvicultural relevance [24].

The possible climatic impacts of large scale tropical deforestation have been investigated in several models. Williams has reviewed the results [26], Molion [27] investigated the energy and moisture fluxes of the Amazon-basin, using the climatology concept of [8]. He divided the water cycle into three systems. The global vapour transport is responsible for 44 per cent of the precipitation; whereas the regional reservoir, and the local soil moisture, supply from the internal cycle 56 per cent of the rain. The self-sustaining system would be interrupted if the retention capacity of forests were missed. In the system analysis, Figure 4, it is demonstrated that there are feedback loops where the response of one part is influenced by the response of the other parts. A positive link means that the parameter causes a proportional change of the sign in the next parameter. A negative link means an inverse proportionality.

Destroying forests will initially increase the surface albedo, reduce absorbed solar radiation at the active surface and change the heat and vapour convection, wind and temperature profiles, cloudiness and precipitation. The loop as a whole is damping, bringing the system to a new equilibrium climatic state. Bernard investigated the influence of the forest evapotranspiration of the Congo catchment and found good correlation between forest cover and the precipitation level [28]. Newell considered the Amazon Forest in relation with the atmosphere's general circulation [29]. Potter used a two dimensional zonal atmospheric circulation model to simulate some of the effects, converting all tropical forest land between 5°N and 5°S to a vegetation type

with an albedo of 25 per cent instead of 7 per cent, reduced evaporation, and increased run-off 30%. The computer results, see Figure 5, indicate an average global cooling of the surface by 0.2 deg C and a reduction in precipitation of less than 1 per cent. However, the reduced convection of latent heat weakens the Hadley-overturning, with cooling in the middle and upper troposphere and increase of precipitation in the latitude bands of 5-25°N and 5-25°S. The meridional transport of heat and moisture out of equatorial regions is reduced, and therefore, with global cooling, a decrease in precipitation between 45 to 85°N and at 40-60°S should follow.

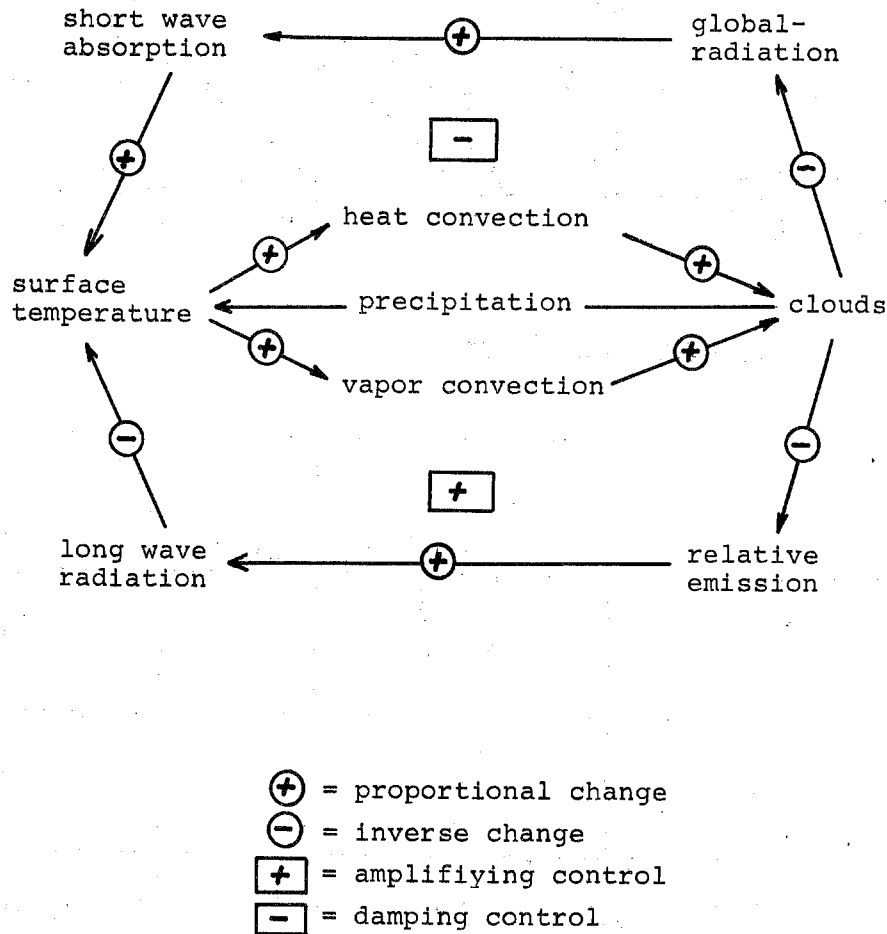


Figure 4: Complexity of interactions and feedbacks after land use change, starting with changes in surface temperature. After Molion (1976).

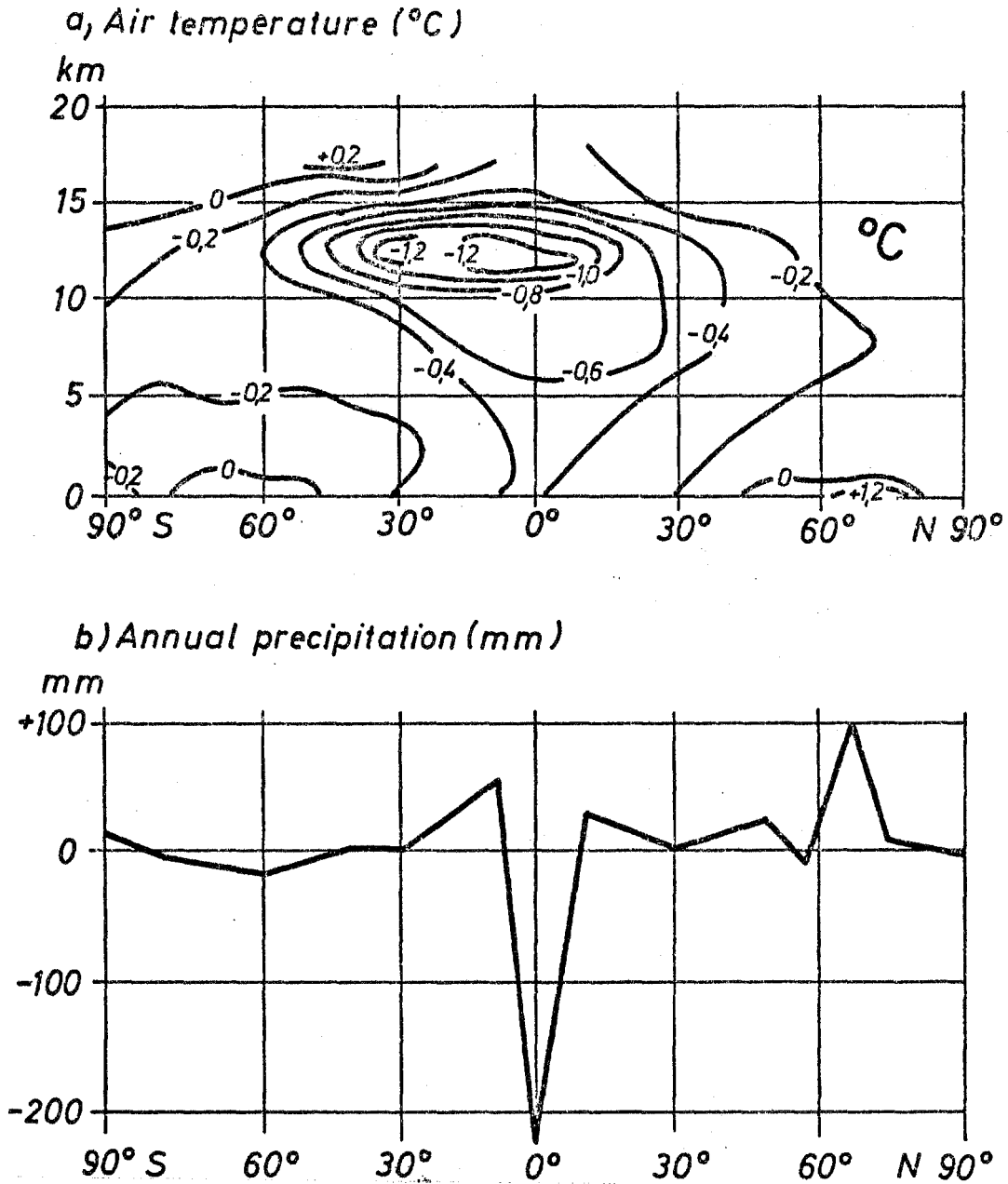


Figure 5: Changes in air temperature and precipitation following deforestation of tropical zone. After Potter (1975).

7.4 Global aspects of deforestation

The above simulations make it probable that such actions may have world wide impacts on the atmospheric circulation; however, one has to be very wary of all the secondary feedbacks, which may introduce compensations into the solid, liquid and gaseous exchanges of the global system. Also one should not overestimate the share of tropical forest areas in the total global biosphere 22. The areal shares (A_t) as a percentage of the surface area of the globe (A_g) are as follows:

	A_t
tropical zone, land and ocean	40 per cent
tropical land surface	12 per cent
tropical forest area	4 per cent

If C_t is the concentration ($G M^{-2}$) of a parameter in the tropical biosphere, then the source power is given by the product $A_t C_t$. Under this assumption the efficiency (E_f) of the influences of the tropical areas may be defined as:

$$E_f = \frac{A_t}{(A_g - A_t)} \cdot \frac{C_t}{C_g}$$

The term C_g stands for the mean concentration of the same parameter in the biosphere of the globe. Using the above percentages of areal representation then the efficiency may be quantified:

whole tropical zone	=	0.67 (C_t/C_g)
tropical land surfaces	=	0.14 (C_t/C_g)
tropical forest areas	=	0.04 (C_t/C_g)

Finally it is of theoretical interest to consider what would happen if the globe were totally deforested. Kirchner evaluated the consequences for the physical terms for the earth-atmosphere interface 10. If forests are replaced by green vegetation, e.g. grassland, then the average albedo of the globe would increase from 18.1 to 18.8 per cent in the northern winter, from 15.4 to 15.8 per cent in the northern summer and from 16.7 to 17.3 per cent for the year. Similar evaluations for the roughness parameter z_0 decreased the global value from 14.9 cm to 3.0 cm. The meridional distributions are shown in Figures 6 and 7. Changing surface drag will shift the angle between surface wind and isobar, influencing the pressure field and with it the general atmospheric circulation of the globe.

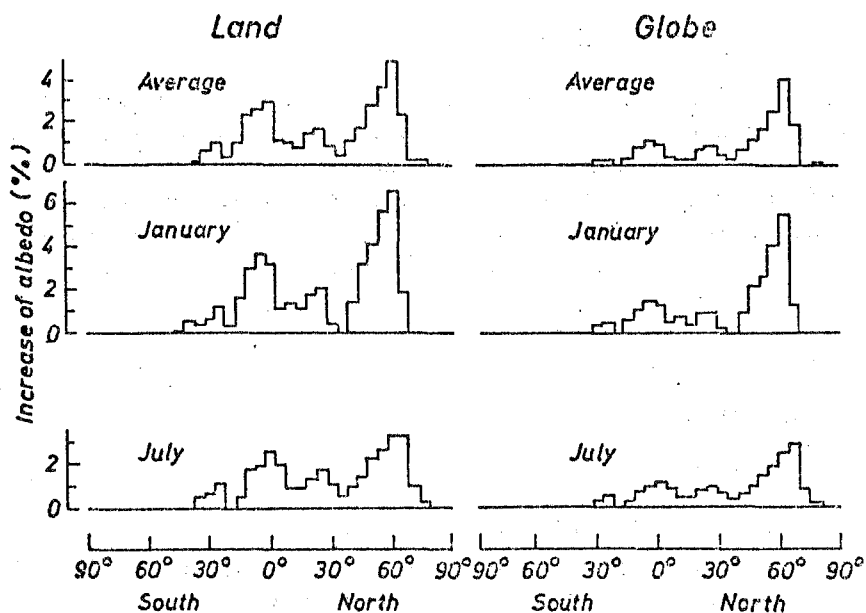


Figure 6: Meridional distribution of albedo changes likely to be produced by total deforestation of earth related to land- or globe-surfaces for January, July or year.

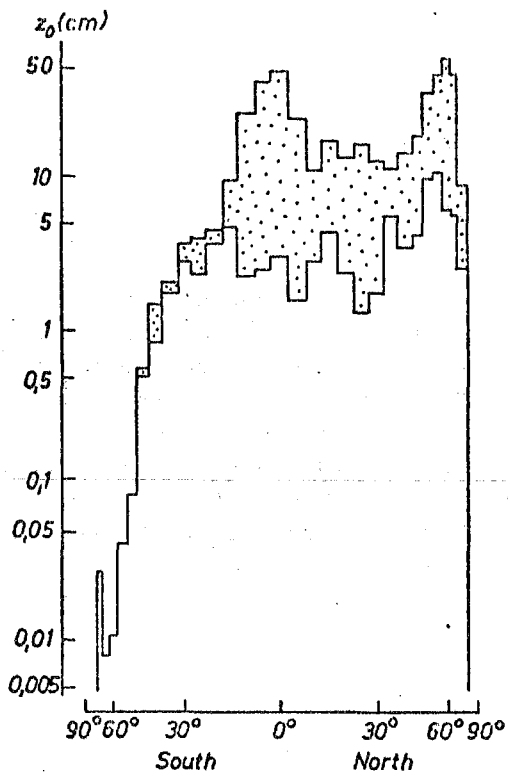


Figure 7: Meridional distribution of change in surface roughness (z_0) by total deforestation of earth.

E. IMPLICATIONS

8. Consequences for forest management and operations

The results of these studies convince us that for many reasons mankind should try to maintain the existing forest cover on the earth. It is possible to manage the forests without drastic consequences for energy, water, and biochemical balances, but the area of forest should not be diminished before we have enough knowledge in order to assess all future consequences.

8.1 Ecological aspects

Forests are mosaics that are needed for the stabilization and aesthetics of a landscape and as part of macroscale ecology. The local and environmental influences of forest are protective for men, plants and animals. They are the favourite areas for the protection of natural biomes and wildlife.

8.2 Economic aspects

Wood, a renewable resource, is reproduced in acceptable amounts, quality, and species diversity only in stable, intact forests. Timber requirements are rising. Climatic fluctuations may disturb local markets, but in the next decades not international supply.

8.3 Social aspects

The use of forest by man and its protective role give forests a social meaning. Pressure of population and the problem of food production tend to reduce forests. This should be done very carefully and only to fixed limits. Forest is used for recreation. Its properties are of high bioclimatic efficiency. Climatic variability and fluctuations are better compensated on the globe if forests cover a great part of the earth surfaces, with good regional distribution - and in balance with the other requirements of mankind.

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CLIMATIC VARIATION AND MARINE FISHERIES[†]

D. H. Cushing*

1. Introduction

It has long been known that fish populations respond to climatic changes; for example herring fishermen say that the herring appear and disappear for long periods. However, much of the evidence has merely a hearsay quality.

Fishes live for one or two decades and in temperate waters the age of individuals can be determined from rings on the otoliths or earstones or from rings on their scales. Thus age distributions are formed from the populations and the youngest age group are called the recruits to the population. Their numbers can be estimated by various means and the magnitude is called the recruitment. The annual number recruiting to the stock balances the annual deaths in the population. The function of the annual recruitment is an exploratory one as contrasted with the conservative function of the stock. Hence it is the recruitment that might be expected to vary with any environmental change.

2. The observed link between climate and fisheries

A fish stock increases or decreases in quantity by variations in the annual recruitment from year to year. Changes in migration pattern might affect quantities of stock, but with one exception (that of the West Greenland cod stock), they can be disregarded. There is a long history of attempts at correlation between the magnitude of recruitment and environmental variables, nearly all of which have failed, probably because one or more of these variables changed its nature at the time of failure; for example wind strength has been used for this purpose irrespective of direction, and the correlation may fail when the direction changes. As will be shown below a relationship might well exist between the magnitude of recruitment and differences in wind strength and direction.

[†] Attached to this paper as an appendix is a contribution on "The Effects of Climatic Change on Inland Fisheries" by R.L. Welcomme.

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There are two important observed links between fisheries and climatic changes. The first relates the variability of year class strength of a single cod stock to a general and unspecified climatic factor. In the second, variations in recruitment to the stocks of many cod-like stocks are summed each year throughout the North Atlantic in the form of a time series of thirty years. Ottestad [1] correlated differences in the recruitment to the Arcto-Norwegian cod stock that spawns in the Vestfjord in northern Norway with differences in the widths of pine tree rings (in *Pinus silvestris*) that grow in the area. As indices of recruitment, catches were lagged by seven years (the mean age of recruitment) to the year of hatching. In the tree ring material, four periods were detected and the components added in each year; the resulting curve was fitted to the lagged catch data by least squares for a period of 85 years. The correlation is shown in Figure 1 and it will be seen that the trend matches the observations equally well throughout the period. Zupanovich [2] has made a similar analysis for an equally long period on the annual differences in catch of the Adriatic sardine. We conclude that the recruitments to the cod stock and to the sardine stock are modified by factors common to fish and tree rings; the common effect of such factors restricts the choice to be made without specifying them. Thus there is a general and unspecified link between annual recruitment and annual differences in tree ring width, probably due to climatic differences.

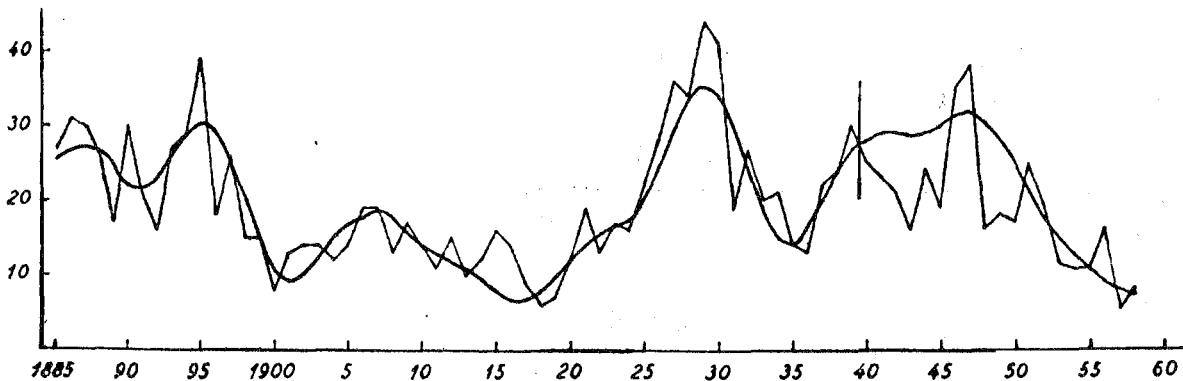


Figure 1: The relationship found by Ottestad [1] between catches of cod (in thousands of tons) in the Vestfjord, lagged by seven years, and a curve constructed from four periods derived from differences in the widths of pine tree rings in the area.

The second approach was made by Templeman [3] who classified the recruitments to ten stocks of cod and herring in the North Atlantic on an arbitrary scale. He found that outstanding year classes in certain years were common to all ten stocks throughout the ocean. For example, the 1904 year class of the Norwegian herring stock with which the recent Norwegian period started (see below) was also an outstanding one for the Arcto-Norwegian cod and the Icelandic haddock. In 1950, all stocks except the Georges Bank haddock yielded outstanding year classes. In a later analysis [4] Templeman showed that the sums of year class indices between 1940 and 1970 showed a peak in 1950 with a subsequent decline (Figure 2). The common year classes across the North Atlantic suggest that the annual differences in those factors that affect the fish stocks are pervasive on an oceanic scale. Hence we should look for

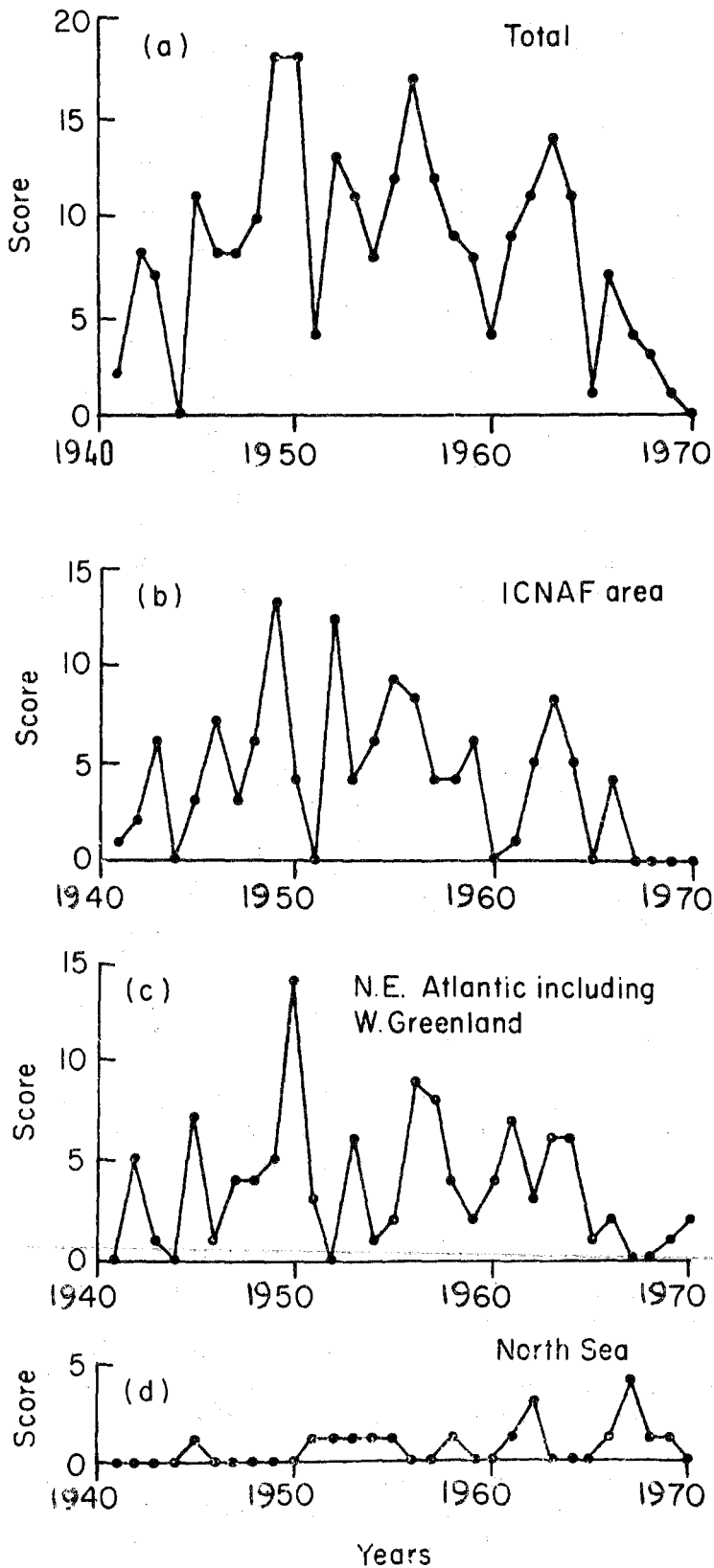


Figure 2: Time series, after Templeman 4, of recruitment indices to the stocks of cod-like fishes in the North Atlantic, the ICNAF area (International North West Atlantic Fisheries Commission) NEAFC area (North East Atlantic Fisheries Commission) and the North Sea. The ordinates are scores based on an arbitrary scale of recruitment.

those factors that affect differences in the widths of ring on pine trees and which at the same time are common to all areas in the North Atlantic Ocean.

3. The effective link during the life history of fishes

Eggs are spawned on the same ground year after year, either in the midwater or on the sea bed. In temperate waters the peak date of spawning is more or less constant in that the standard error of its mean is less than a week [5]. The larvae drift away from the spawning ground, which is constant in position from year to year, to their fixed nursery ground, a beach or a shallow bank, and during their larval drift they grow into the production cycle or spring outburst of plankton, as shown by Cushing [6] for the herring populations in the North East Atlantic. The spring outburst in temperate waters varies each year in amplitude, spread and time of onset [7] due to annual differences in wind strength and direction [8] and in solar radiation [9]. The rate of production of the planktonic algae is governed by the ratio of the depth of the euphotic layer to the depth of mixing, which has been called the production ratio. As spring proceeds, the euphotic layer deepens with the rising angle of the sun and the depth of mixing becomes less as the wind stress slackens. The larval drift is a period in the life history when physical factors such as wind strength and solar radiation can affect the food available to the growing larvae.

It is possible that the magnitude of recruitment is not determined during the larval drift but on the nursery grounds on the beaches or on banks in relatively shallow water. However, that magnitude for a number of fish species is probably determined during the first year of life long before the recruiting fish leave the nursery ground to join the adult stock. Indeed such information is regularly used in the International Council for the Exploration of the Sea for the annual assessment of quotas in the Northeast Atlantic. But the effect of physical factors on the magnitude of recruitment will be harder to discern on the nursery ground if only because the fish are growing continuously on food which is like the adult food and may well be unlimited. The evidence for this is that density-dependent growth in fishes is restricted to the juvenile part of the life cycle, the first year in herring and the first one or two years in haddock. In the larval drift, however, in temperate waters, the variation in time of onset of the production cycle, the spring outburst, is due to well defined physical factors and may lead to annual differences in quantity of food available to the larval fish. Thus, preliminarily, the larval drift is the period in the life history when the magnitude of recruitment might be determined.

4. The recent warm period

The recent warm period is conveniently shown in the trend of mean surface air temperatures in the northern hemisphere as deviations from the mean of five year periods between 1880 and 1969 [10]; such anomalies increased to a maximum of 0.4 deg C in about 1945, after which they declined. Similar trends have been observed in the sea-surface temperatures in the Northeast Atlantic. The recent decline is associated with weakened westerlies over the British Isles and amplified long waves in the northern hemisphere. Considerable biological events have occurred during this period and it is unlikely that the small differences in temperature have played a direct part in them. It is more probable that the trends in temperature indicate changes in other factors including wind strength and direction and solar radiation at the sea surface together with advective changes in oceanic currents.

The period of warming was associated with the appearance in higher latitudes of some of the larger and more conspicuous animals from the south. During the decade 1925-35, subtropical animals appeared off California, in the Bay of Fundy, off the western coasts of the British Isles and as far north as the Färoe Islands and Iceland. Boreal forms (those of temperate waters) appeared off West Greenland, north and east of Iceland, off Svalbard and off the Murman coast. Such records do not represent the movement of populations but the appearance of strays from the normal migration circuits. Fish migrate regularly over considerable distances, in thousands of km y^{-1} ; indeed as Otsu [11] has shown, albacore have been observed to cross the Pacific in less than a year. Cod have crossed the Atlantic from one stock region to another [12, 13] and such stray from the normal streams of migration is to be expected. The widespread appearance of strays across the northern part of the North Atlantic suggests that the circulation of the ocean intensified during the decade when they were observed. Thus migration patterns were probably not disturbed, but the spread of strays would have been noticeable to the north with a more intense circulation.

The most dramatic invasion during the period of warming was the rise and fall of the West Greenland cod fishery. During the late nineteenth century no cod were caught on the offshore banks during various exploratory voyages. On the Tjalfe expedition in 1908-10, a few were found there and in 1912, 24 tons were taken. Annual catches were recorded in a northerly progress as follows: Julianehaab (60°N) 1917; Godthaab (64°N) 1919; Sukkertoppen (65°N) 1922; Holsteinsborg (66°N) 1927; Disko (68°N) 1931; latitude $72^{\circ}45'\text{N}$, 1936 (Figure 3). The stock was established off West Greenland with a series of strong year classes, 1917, 1922, 1926, 1934 and 1936, and by the thirties annual catches had built up to 70 000 tons. It is obvious that the northerly progress took place as the new year classes growing up in West Greenland became established. Later year classes, 1945 and 1949, increased the stock again until catches in the fifties and early sixties reached as much as 450 000 tons. The last good year class appeared in 1963 and the last significant one in 1968; in recent years, catches have been banned off Greenland. The history of the fishery follows the recent period of warming fairly closely, the most abundant year class of all having appeared in 1949, after which a decline set in. In broad terms the colonization of the West Greenland offshore banks occurred during the period of warming, but the mechanisms were more complicated than a simple increment of temperature.

In the first decade of the century, to judge from Schmidt's distributions of cod eggs and larvae off the west coast of Iceland, it is unlikely that many drifted across the Denmark Strait towards Greenland. During the Norwestlant Expedition in 1960-62, cod eggs and larvae were found spread across the Denmark Strait towards Greenland [14]. The later distribution is much more extensive, either because the stock was larger or because the Irminger current was stronger. The two possibilities cannot be separated.

A remarkable tagging experiment executed during the thirties [15] illuminated the mechanisms involved. Cod tagged off West Greenland were recovered in the Iceland spawning fishery as mature fish. Although a number of fish tagged in the Icelandic fishery migrated back to Greenland between 1934 and 1945, none did so since then. In general, the Icelandic spawning fishery has been sustained to some degree by the

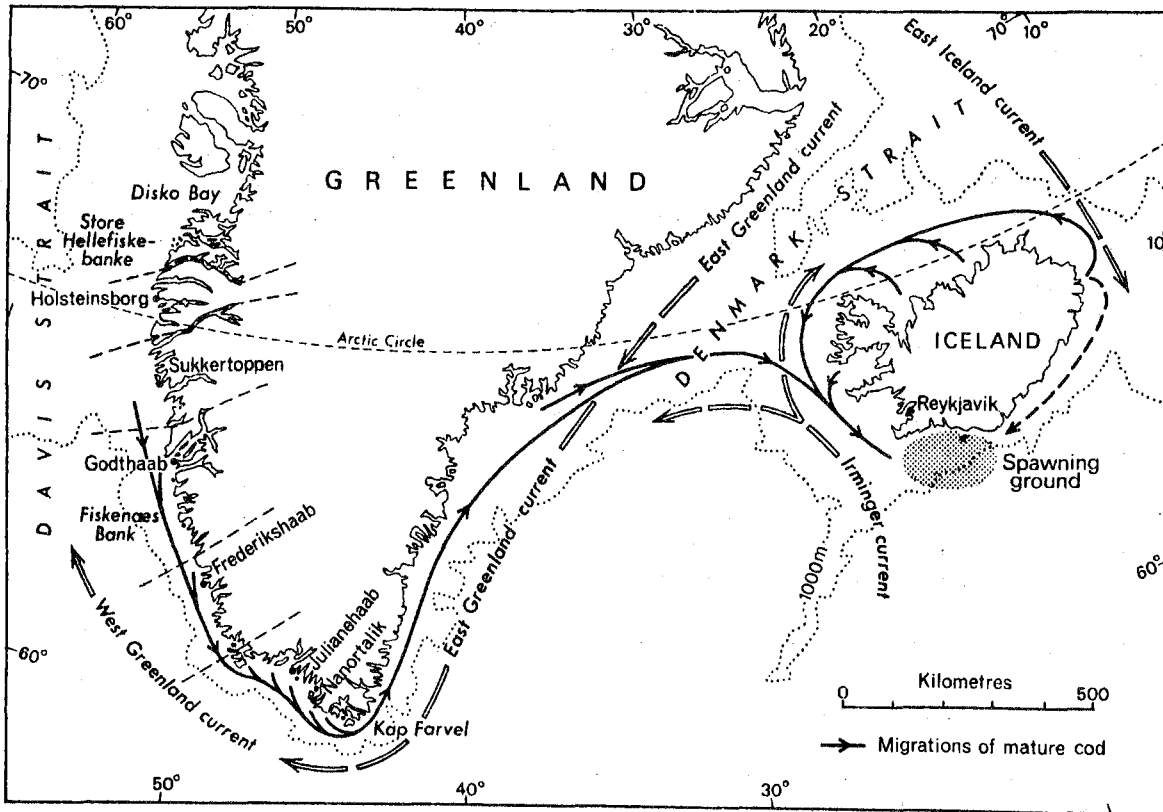


Figure 3: Chart of the Iceland-Greenland area showing the currents and the possible migration routes of cod and larvae between Iceland and West Greenland 29.

immigrant Greenland fish; probably between a quarter and a half of the Icelandic spawning stock during the period of warming was sustained by the Greenland immigrants. Thus there was a double link between the two stocks, the drift of larvae in the Irminger current from the spawning grounds inside the Westmann Islands to Cape Farewell and West Greenland and the permanent migration of adults from West Greenland to the spawning stock at Iceland (Figure 3). Yet a proportion of the stock remains off West Greenland as the stock was in the process of isolating itself from the Icelandic one from which it originated and which sustained it.

The decline of the West Greenland stock may be demonstrated by some discoveries of Dickson et al. 16. Between the decades 1930-39 and 1956-65, a shift of the Icelandic low to a mean position well south of Greenland generated easterly winds across the Denmark Strait. But by the later decade, 1966-75, the Icelandic low shifted in position again and generated northerly winds in the Denmark Strait, thus possibly making it difficult for the cod larvae to travel from Iceland to West Greenland. If we extend the argument to the whole period of the existence of the West Greenland cod fishery it would imply persistent easterly winds across the Denmark Strait for a long period, perhaps together with an intensification of the Irminger current.

The life of the West Greenland cod fishery between 1920 and 1970 represents the most dramatic movement of animals into high latitudes as a result of a succession of closely spaced year classes. Collapse was relatively sudden and only the older fish were left to survive, but the existence of the stock off West Greenland may have depended rather critically upon meteorological events. Figure 2 shows the total recruitment to the stocks of cod-like fishes in the North Atlantic between 1941 and 1971, including those at West Greenland. First it will be seen that the general trend of recruitment like that at West Greenland was to rise to a peak in 1949 or 1950 after which it tended to decline. So in general as the North Atlantic became warmer the stocks of cod-like fishes became more abundant and as it cooled they tended to become somewhat less numerous.

During the sixties another event took place. The 1962 year class of haddock in the North Sea was twenty five times larger than the previous average (for a long time period). Since that date the recruitment of all cod-like fishes in the North Sea, cod, coalfish, whiting, haddock and Norway pout, has increased considerably. The total yield of such fishes has increased by three times and the stocks by nearly an order of magnitude ^[17]. The increase in the North Sea has followed the decrease at West Greenland almost consecutively. At one time such events might have been interpreted as a southerly migration but today they are seen as a decline in the north, followed by an increase in the south. Indeed we might expect the fishery in the Barents Sea to close down if the period of cooling were to continue.

There are thus two forms of biological event associated with the period of warmth. The first is the appearance of straying conspicuous animals in northern waters as the circulation might have intensified. The second is the variation in abundance at different positions in the North Atlantic, a decline since 1950 off West Greenland and an increase in the North Sea since the early sixties. Dickson *et al.* ^[18] have established a correlation between the abundance of cod stocks in the North Sea and declining sea temperature. Such events are to be expected in each region of the world ocean as prevailing winds shift in strength and direction across the decades with associated changes in solar radiation at the sea surface.

5. Long term periods

The recent warming lasted about ninety years or so from 1880 to 1970 with a peak in 1945 and during these years the fishery for the Norwegian herring flourished. There is a well-known alternation between this fishery and that for herring off the Bohuslan coast of Sweden which traditionally occurred in cooler times when the Baltic froze in winter. Records of the presence and absence of the two fisheries extend back to the fifteenth century and earlier indications may be found in the Icelandic sagas.

Figure 4 shows the alternation between the Norwegian and Swedish fisheries; also given are the periods of high catches in the Japanese sardine fishery which appear to correspond with those of the Norwegian herring. Variation in catches of the Hokkaido herring do not correspond with either those of the Norwegian or the Swedish herring. Anchovy and sardine scales have been collected from anoxic sediments (so they are well preserved) off California ^[19]. The record of sediments extends back for two thousand years and suggests that the recent sardine period was concomitant with the last Norwegian herring period. Indeed, Zupanovitch ^[2] has established

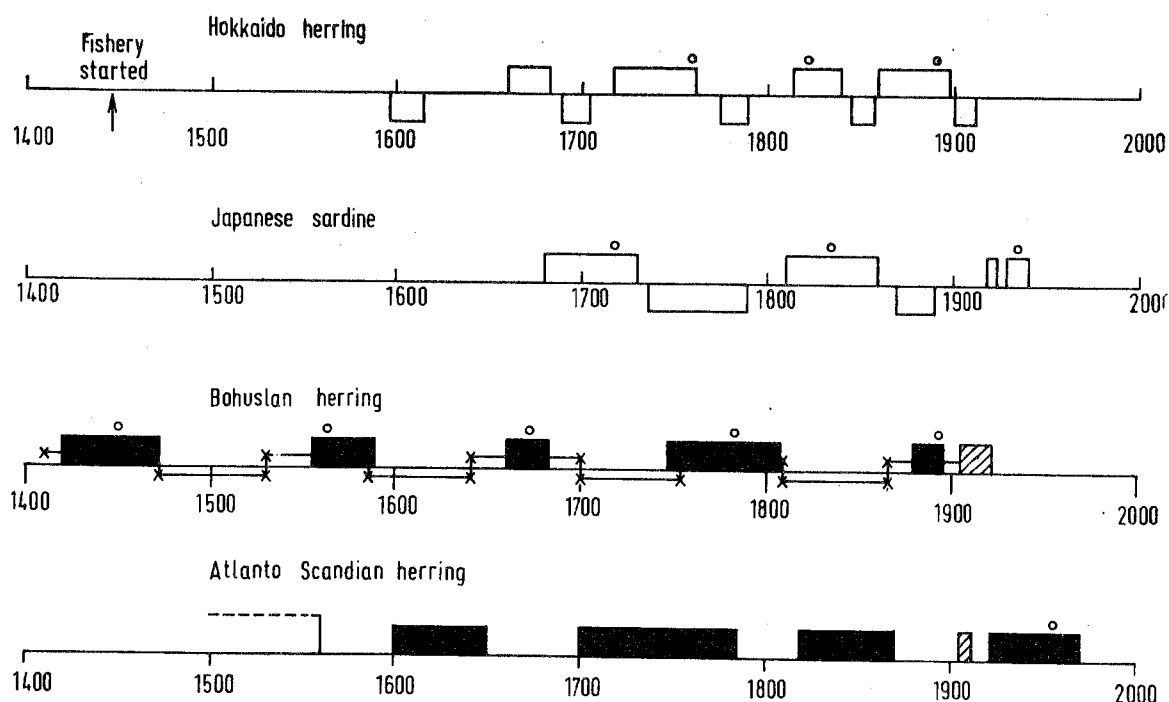


Figure 4: The periods of presence and absence of the Norwegian and Swedish herring fisheries which have alternated since the fifteenth century; the regular 55 year period was fitted by Ljungman (1881) to the data. Periods of high and low catch in the Japanese sardine and Hokkaido herring fisheries are also given $\frac{10}{}$.

that catches of sardines off Japan, California, Spain and Yugoslavia between 1905 and 1960 reached peaks in the thirties, forties and fifties as if associated with those of the Norwegian herring. Similar trends are given in the indices of recruitment to the cod-like fishes from 1941-71 as shown in Figure 2. Thus the recent period of warmth can be described in the periodical trends of a number of fisheries throughout the world, which may be characterized more generally as "Norwegian herring" periods.

The recent warm period, which can be shown by atmospheric temperature anomalies in the northern hemisphere or by the distribution of westerlies across the British Isles, appears to be indicated very clearly by fluctuations in the fisheries. The climatic fluctuation is not of great amplitude but those in the fishery are, as if they rectified the periodicity. Figure 4 shows secular records for nearly five hundred years and a period of about a century or so is revealed. The relation between the fisheries and the recent warm period is established fairly clearly, but the correlation between the fishery periods and climatic change cannot be established in the same way because of the lack of instrumented information. However, this does not mean that the material from fisheries should not be used in the future.

The recent warm period had effects not only on an array of fish populations, but also on the marine ecosystem. Between 1925 and 1935 a series of changes occurred in the ecosystem of the Western English Channel which reversed in 1965-75, the

Russell cycle [20]. It is a particularly valuable series of observations not only in time but also in position because the area lies on the southern edge of the boreal zone where such changes might be expected; a comparable position in the Pacific would lie between the cyclonic Alaska gyral and the North Pacific anticyclone. Hence, although analogous changes might be expected elsewhere, for example in the North Sea or in the Norwegian Sea, they might not be so dramatic. Essentially the ecosystem changed between 1925 and 1935 from one dominated by herring, macroplankton, and fishes to one dominated by pilchard and small zooplankton, a most thoroughgoing change of structure (Figure 5).

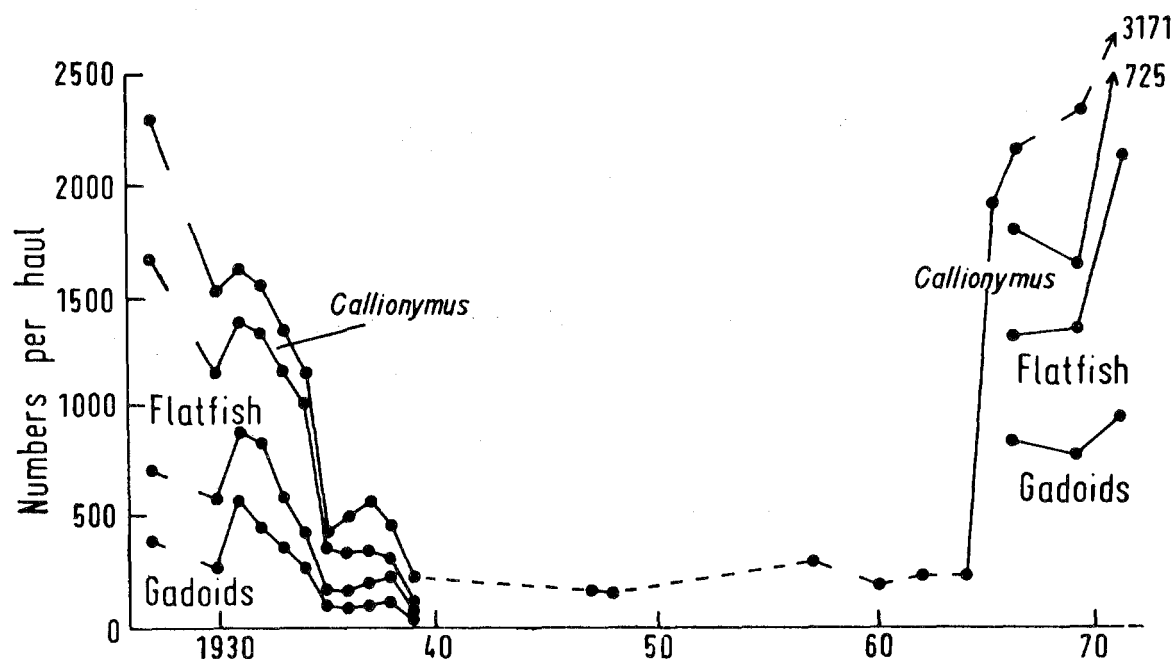


Figure 5: The Russell cycle or the changes in the marine ecosystem in the Western English Channel [20].

In more detail, in 1930-31 macroplankton was reduced by a factor of four and the winter phosphorous maximum was reduced by a third. The local herring population lost its recruiting year classes from 1926 onwards (the year of hatching) and the fishery on old surviving fish ended in the late thirties. Pilchard eggs were first noticed in the plankton nets in 1926 and became common in later years and reached high numbers (in thousands in the nets) by 1935. The larvae of spring spawned fish larvae were reduced sharply in 1931 as were those of summer spawned larvae in 1935 [21]. In the decade 1965-75 the changes were reversed; macroplankton and winter phosphorous increased in 1971, but the fish larvae increased again between 1966 and 1970. The numbers of pilchard eggs were reduced at the same time, but no herring fishery became re-established although herring catches were made sporadically in the early seventies. There is some evidence that the cycle of events observed in the first decade was reversed in the second.

The changes in the marine ecosystem as displayed by the Russell cycle occurred during the recent warm period and could be interpreted as a switch from a northern form, characteristic of the North Sea or Norwegian Sea, to a southern form such as might be found off the coasts of Spain and Portugal. In other words the changes superficially resemble those involved in the northward spread of conspicuous animals which was characteristic of the decade 1925-35, when the Russell cycle first started. Further, the abrupt nature of the changes at the start and at the end of the cycle recalls the sudden appearances and collapses of the Norwegian herring fishery. Thus, we conclude that not only can the fish populations switch their abundances by orders of magnitude but also the marine ecosystem can alter its structure; because both events occurred during the recent period of warming, starting as it began and ending as it finished, we are led to believe that such switches are linked to climatic change.

Let us consider how a population might switch its abundance by orders of magnitude. Figure 6 shows the theoretical dependence of annual recruitment on parent stock, which takes the form of a convex or dome shaped curve 22. Normally any perturbation or annual recruitment will tend to return the stock to the point of stabilization at which the curve cuts the bisector (recruitment and stock being here expressed in the same units). The shape of the curve provides resilience to the stock in its response to perturbation: the return time is short when the curve is dome shaped and is long when the curve is merely convex. In cod-like fishes the curve is dome shaped and stocks of such fishes resist environmental change because the return time is short; in herring-like fishes the curve is lightly convex; the return time is long and such fishes cannot withstand environmental changes and must respond to them. The figure shows how if there is a sequence of recruitments at low stock ("a") which lie below the bisector, the stock will move towards the origin. Similarly, a sequence of high recruitments above the bisector at stock higher than that at the stabilization point ("b") will generate large increases in stock. Thus, in principle at least, a mechanism exists by which fish populations may increase or decrease by orders of magnitude and it may provide the rectifying character observed in the clupeid populations through the centuries. In the next section a mechanism will be proposed by which the variability of recruitment can be described at least in temperate waters.

An ecosystem such as that in the Western English Channel comprises a large number of numerous populations, say fifty to a hundred. The changes in the Russell cycle are of course changes in population, for example herring and pilchard such as might be described by the mechanism displayed in Figure 6. However, the most remarkable changes in the Russell cycle are changes in structure, i.e., the decline of herring preceded the rise of the pilchard, but the concomitance suggests a link between the two events which in this case might be competitive, but need not be. The mechanism which may describe the variability of recruitment in the next section may provide a basis on which changes in structure as shown in the Russell cycle might take place.

6. Short term periods

Short term periods have included annual fluctuations within decades or parts of decades. Amongst fish populations there are now available series of recruitments to a number of well known fish stocks for some decades (Figure 7). Most are estimated

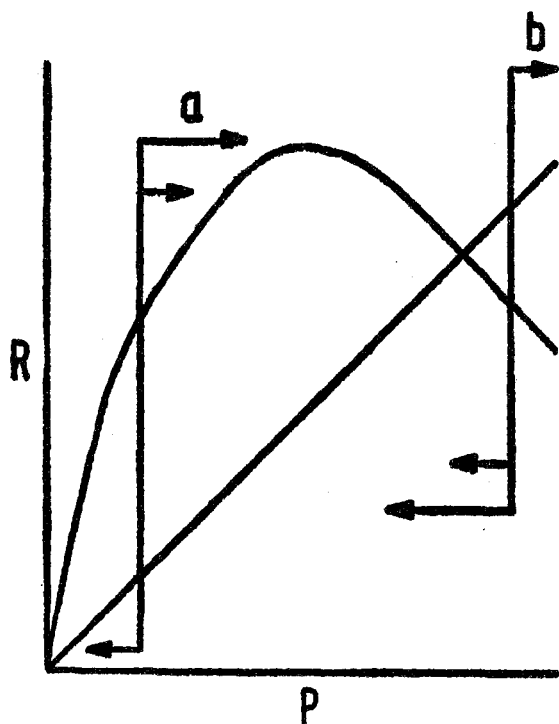


Figure 6:

The dependence of recruitment in numbers upon the parent stock in weight; the stock stabilizes where the curve cuts the bisector. At low stock a sequence of very low recruitments would reduce stock quality by some orders of magnitude and at high stock a sequence of very high recruitments would increase stock 30.

by cohort analysis 23, which is a method of calculating stock from catches at age in numbers; that for the Norwegian herring was calculated by summing the catches by age groups 24 and that for the Karluk river sockeye salmon was estimated from the escapements (i.e. the stock that is about to spawn) 25. In general the stocks examined are those of the abundant stocks of herring and cod-like fishes and most time series extend for a number of decades; indeed that for the Karluk River sockeye salmon extends for eighty-five years. In general, the variation in recruitment is about one order of magnitude although that of the salmon is less and that of the Norwegian herring is greater. Fish live quite a long time and the stock has a conservative purpose in that it averages the annual recruitments for a number of years. Another way of expressing the same idea is to point to the exploratory function of recruitment as if the stock were sampling the environment of food and physical factors.

In more detail, the time series of recruitments to the stocks of herring show upward or downward trends. The latter in the Downs stock of herring was probably due to overfishing, as was the collapse of the Norwegian herring, although Devold 26, might have expected a collapse due to natural causes within a decade or so. But the rising trends and perhaps some falling ones reflect a slow adjustment by the stock to the environment during a period of years. By contrast the time series of recruitment to the stocks of cod-like fishes fluctuate about mean values for decades. As noted above, the shapes of the stock-recruitment curves of the two groups, herring-like and cod-like fishes, differ, and where the latter have to respond to environmental differences whatever they are, the former tend to be insulated from them.

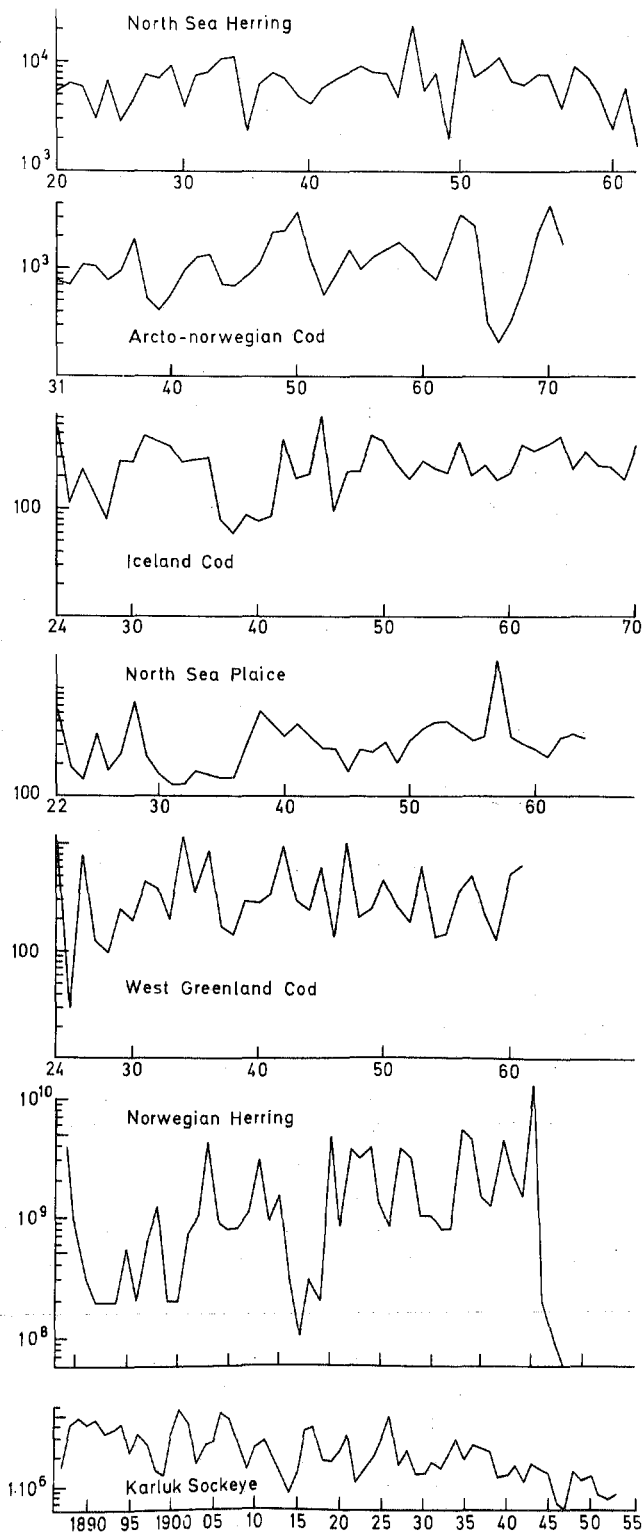


Figure 7: Time series of recruitment estimates in numbers for cod-like fishes (by cohort analysis), herring (by cohort analysis and by the method of virtual populations) and the Karluk river salmon (by escapements) 23.

In temperate waters fish tend to spawn in spring at a fixed season as noted above. Although the spawning season may extend for a long time, two or three months, the peak date of spawning is nearly the same from year to year for plaice, herring, salmon and cod [5]. In the upwelling area off California, however, spawning of sardines and anchovies is spread across months. The question then arises how the fish stocks exploit the food available in temperate waters and in upwelling areas.

In temperate waters larval food is produced during the spring outburst, the time of onset of which is variable. In Figure 8 the match or mismatch of larval production to that of their food is displayed in diagrammatic form. In temperate waters eggs are produced at the same time each year but the subsequent production of larvae varies with temperature because their development rate depends inversely on temperature as a power function. Hence we would expect production to be accelerated a little in warm water but in cold water it would be considerably delayed. The production of larval food is highly variable as it is generated during the spring outburst and hence the timing of production of larval food depends upon wind stress and direction and upon solar radiation. Figure 8 shows the distributions in time of the production of fish larvae and their food with indications of spread in time. They overlap, and if the degree of overlap is high, they are matched and recruitment may be high because the larvae do not lack food; conversely, if mismatched, a poor year class may appear through food lack. The figure also shows a difference between high and low stock which suggests that the chance of mismatch is increased at low stock and that the variability of recruitment is observed to be higher at low stock. The hypothesis that recruitment variability can be accounted for in the match or mismatch of larval production to that of their food has not yet been tested, but it is amenable to experimental modelling; indeed models of the production cycle in the sea have been available for a long time.

Figure 9, from a paper by Glover et al., [27] shows changes expressed in standard measure in zooplankton in the North Sea and the North Atlantic between 1948 and 1972; the information was collected in monthly samples from the plankton recorder network. The recorder is towed by merchant vessels on fixed routes across the North Sea and North Atlantic. The figure shows that the number of copepods and zooplankton biomass has declined during the period. It also shows that the time of onset of the spring outburst has been delayed by three weeks or a month in the North Sea; such a delay might be associated with the outburst in cod-like fishes that started in 1962. If the match-mismatch hypothesis were true, a shift in the time of onset of the spring outburst of this degree might well lead to an improved match and hence enhanced recruitment.

In upwelling areas fish spawn when food becomes available. Sardine-like fishes feed on planktonic algae at this time, which is inefficient in energetic terms. They probably do so to allow their subsequent larvae to grow on the subsequent zooplankton. Then the signal to spawn is merely the production of algae. The timing of upwelling, wherever it occurs, depends upon the appearance of longshore winds blowing equatorwards. Hence the fish populations have solved their timing problem in the upwelling areas [17].

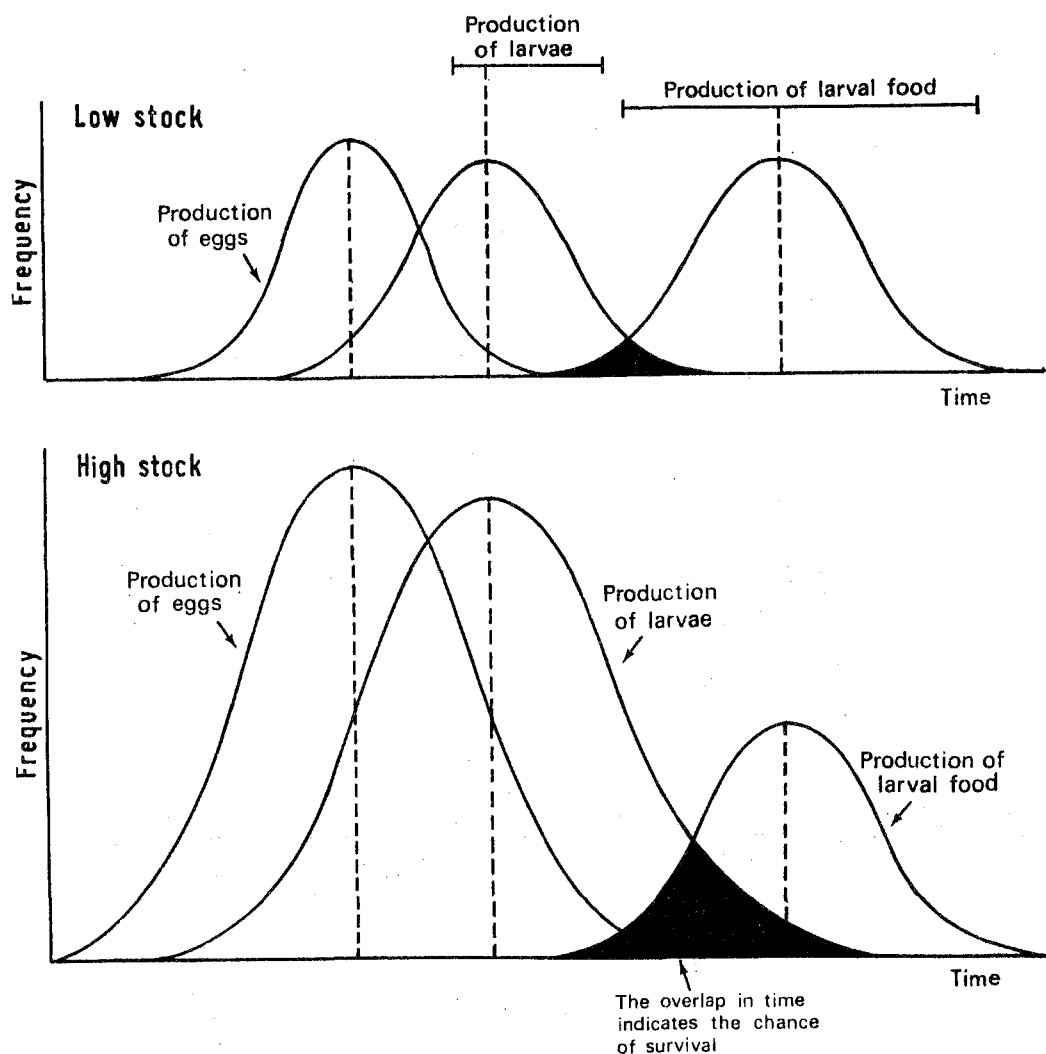


Figure 8: The match (or mismatch) of larval production to that of their food in the spring outburst of plankton. The production of larvae is accelerated slightly in warm water but is very much delayed in cold water; the production of larval food varies considerably in time of onset. The overlap between the two distributions represents the degree of match or mismatch which is less spread at high stock than at low stock [29].

The appearance of El Niño off Peru every five or ten years has had profound effects on the great anchoveta fishery there (see also overview paper by Hare). El Niño is a warm current which appears at or after Christmas and in which the rate of carbon production is reduced by two thirds. Following the El Niño of 1972-73, the catches fell from 12 million tons to less than 2 million tons with disastrous consequences in Peru. The fall led to a sharp increase in the world price of fishmeal.

Considerable researches by meteorologists and oceanographers from Jakob Bjerknes onwards have led towards understanding the trans-Pacific nature of the

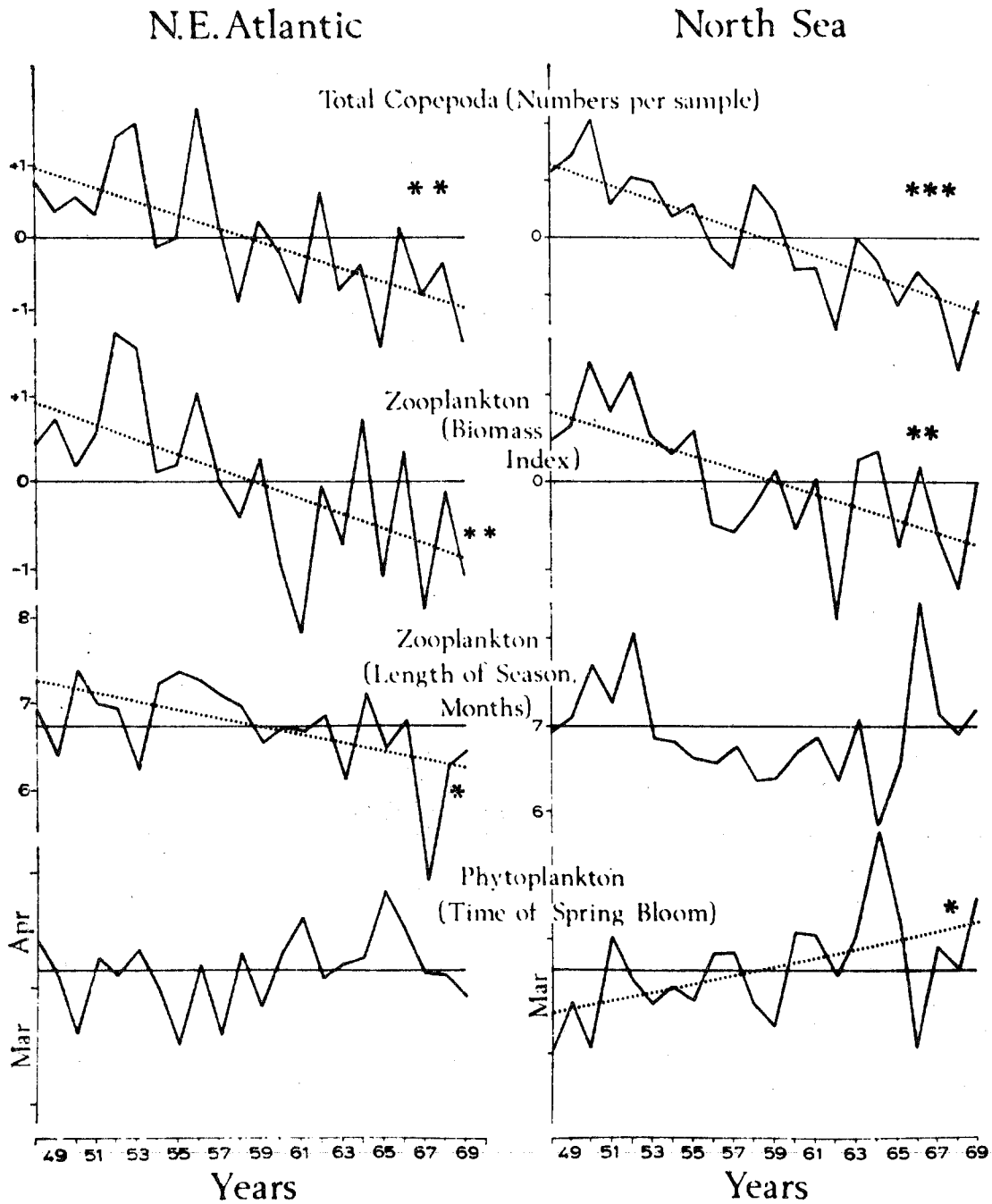


Figure 9: The decline of zooplankton biomass and of copepod numbers in the North Sea and in the North Atlantic between 1948 and 1951; a delay in the spring outburst of up to a month is also shown. The ordinate is given in standard measure, a unit of the standard deviation. Linear regressions are fitted to the data [27].

origins of El Niño, which is the transequatorial flow between the Peru Oceanic Current and the zone of coastal upwelling. Indeed it is now possible to predict the occurrence of this warm current some months ahead by three distinct mechanisms which are linked. But it is not yet possible to forecast the magnitude of the phenomenon for the degree of warm water flooding off Peru varies from event to event.

There has been a large population of guanay birds in Peru, cormorants, boobies and pelicans, on which the guano industry is based. When El Niño appears the birds abandon their nests and fly to Ecuador or Chile; young and adult birds suffer considerable mortality and the population has to recover from this effect. At the start of the fishery the bird population recovered from the El Niño of 1957-58 in three years or so. However, when the catches had reached several million tons, in the next El Niño of 1965 the number of birds was reduced from 18 million to 4 million and after that of 1972-73 it was further reduced to 1 million. Thus birds have suffered in competition with fishermen, and indeed the Peruvians have suffered great reductions in two industries, fishing and guano, as a direct effect of El Niño.

An interesting point is that recruitment in the period 1965-70, after the bird population was first reduced, was increased by a factor of 1.6 as compared with that in 1960-64. This suggests that the recruiting anchoveta are normally eaten by young birds which remained in Peru after the adults had migrated after the breeding season. The 1971 year class of anchoveta, before the great El Niño, failed perhaps because part of the parent stock failed to mature fully during the spawning season; it may have been a density-dependent delay caused in fact by recruitment that was unexpectedly high. Then the subsequent year classes of 1972 and 1973 were sharply reduced either because the El Niño was an event of greater magnitude than had been experienced in the fishery or because the stock had been reduced by the failure of the 1971 year class. El Niño usually enters Peruvian waters in two floods in eighteen months, each in the early months of the year. There is then a regression in August, September and October, the period when the main spawning of the anchoveta takes place. Hence in the two earlier El Niños in the period of the fishery the eggs and larvae might have been released during the regression when upwelling might well have continued. If this interpretation of the consequences of El Niño is right, it disturbs the predator/prey relationship between bird and anchoveta already disbalanced by the fishery. If the bird population had recovered more quickly than the anchoveta, the events of 1972-73 might have become irreversible.

The short term periods are really those generated by differences in recruitment from year to year. It is possible that in temperate waters such differences depend on differences in wind strength and direction and in solar radiation at the sea surface at particular positions where the larvae grow. In the upwelling areas such differences might be minimized because of the way in which the fish exploit the production processes; but if the wind shifts its direction, the area of upwelling might change as it might have in the past as compared with the present as shown by phosphatic deposits [28]. Lastly, El Niño is predictable; but we need to be able to foresee its magnitude.

7. Conclusion

The events in fisheries in recent decades have been used to indicate the ways in which the biological production of the world ocean might be modified by

climatic factors. Some evidence was produced to show that at least one marine ecosystem changed its structure, presumably as a consequence of changes in the constituent populations. The annual changes in recruitment to a single population of fishes vary by about an order of magnitude. It was suggested, but not shown, that such differences would be generated by differences in wind strength and direction, in solar radiation at the sea surface and in sea surface temperature at the somewhat restricted areas where the larval fishes grow i.e., between spawning grounds and nursery grounds. Such information can be handled in experimental models in the first place to discover whether the production cycle can be shifted in time of onset, as has been observed in the North Sea and in the North Atlantic. The dependence of recruitment in detail upon the proposed climatic factors can be investigated in the same way, but also with the more general relationships between recruitment and parent stock.

The longer term periods are generated by the same hypothetical mechanisms but the events are arranged in a different way. When the stock of Norwegian herring is reduced by some orders of magnitude at the end of its period of abundance, there is perhaps a sequence of mismatched year classes which causes the drop in stock. But, further, when the stock has been reduced one would expect that the mismatched condition would remain right through the period of scarcity. Then for those responsive stocks like the herring one would expect to be able to define conditions of match distinct from those of mismatch, which may apply to a lesser degree to the more resilient stocks of cod-like fishes. The use of the experimental models described above might in the future be extended to cope with such persistent changes in match or mismatch.

In Figure 9 is shown a decline in zooplankton in two decades in the North Atlantic associated with a delay in the spring outburst. Much of this paper describes the possible dependence of this form of change upon climatic changes and so one might expect that the productivity of the oceans also depends upon them. There are three possible developments:

- (a) general changes in biological production in the sea might be related to climatic factors;
- (b) it might become possible to forecast the outstandingly high and low recruitments merely by relating climatic factors to the spring outburst in temperate waters;
- (c) because the fish populations appear to rectify the very low amplitudes of climatic periods, their variability might be of use to climatologists.

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Appendix : 1

A P P E N D I X

THE EFFECTS OF CLIMATIC CHANGES ON INLAND FISHERIES

R. L. Welcomme*

1. Introduction

The fisheries of inland waters are mostly located on relatively small bodies of water, or on water courses that are sensitive to changes in climate. Lakes can increase or decrease in size, and rivers may be swollen by floods or reduced by droughts to the advantage or detriment of the fish species contained therein. Many such changes have taken place during the last few decades and the corresponding effects on the fish populations have been observed. The severity of some of these changes, such as those that took place in the Sahelian rivers of Africa in the early 1970s have given cause for concern and future policies for the development and management of this region rest heavily on assumptions as to future climatic patterns. Fisheries are not the only users of the world's inland waters, and the increasing demand for water for a great variety of purposes is creating a situation where the equilibrium of supply is increasingly liable to be upset by even minor changes in any one of a number of climatic parameters. Some of the information available has been assembled in this paper in order to assist in assessing the impacts of recent changes in climate on inland fish production.

2. Effects of Climatic Factors on Fish

Various climatic factors may operate upon fish, either directly through their physiology, or indirectly through modifications to the ecosystem. Most notable, perhaps, of the direct reactions are those resulting from changes in temperature. The growth of individual fish is closely allied to the temperature of the water. Improved growth in warmer water arises both from the higher primary productivity of waters at higher temperatures and from the internal physiological processes of the fish which proceed at a faster rate. Cold season checks to growth are well known in species from temperate waters, and with reason; the warmer the water and the longer the duration of the warm period, the better the growth of the fish. Temperature is also closely linked with breeding behaviour. Many species will not breed until the water warms beyond a certain point; others require a drop in temperature to come to maturity and reproduce. Other climatic factors, such as the degree of insolation, are influenced by cloud cover, or climate-dependent environmental variables, such as changes in water quality and quantity associated with rainfall. These factors can act as physiological stimuli, particularly for the timing of the onset of reproduction. Fish have poor breeding success in years in which the appropriate conditions are not fulfilled and if several bad years are bunched together, as they often are, longer term changes in the abundance or even the distribution of the species can result.

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Indirect effects, where the climatic factor influences the environment in which fish live, are more numerous. The principal factors are those which determine the area of water or living space available to the fish. Many lakes in the tropics are well known for their periodic expansions and contractions. Such fluctuations in level can change not only the productivity of the water bodies in terms of fish catch, but also the whole structure of the fish community which lives in them. Most riverine fish populations depend on the floodplains associated with the river for feeding and breeding during the wet season. The catch of fish in the flood zones has been directly correlated with the intensity of the floods in previous years, higher floods in one year giving better catches a year or two later 1. The response of fish to flood conditions is not only dependent on the quantity of the flood, but also on the form of the flood curve and its timeliness. Even slight changes in rainfall patterns can sufficiently disturb the pattern of flooding as to create differences in the effectiveness of reproduction. There are indeed many species that either fail to breed or where the young fail to survive in years of delayed or insufficient flooding. This, together with the ability of other species to adapt to changes in conditions, can lead to quite extreme changes in species composition within the fish community. Conversely effects have been observed in lakes as well as in floodplains or swamps where higher than normal floods have produced a surge of production. In these cases there is, of course, an increase in general productivity because of the nutrients released from the newly flooded land, but there is also an increase in new habitats, lack of which may have been limiting to some species as nurseries or breeding grounds.

Needless to say, long-term climatic change (over millennia) has been implicated in speciation and in the disappearance or extinction of many stocks of fish. Equally, climate-induced changes in vegetation cover can alter the whole nature of a river system, changing it, for example, from a forested river to one of savanna type. Fish communities inhabiting the two types of system are very different, not only in terms of their species composition, but also their productivity patterns. Such arguments may seem of only intellectual interest, but in fact, there is much doubt as to the suddenness with which such climatic changes occur.

3. Case Histories

As examples of the ways in which these mechanisms, work, let us take two cases from Africa. Here the fish communities concerned form the basis for important fisheries, and the waters, in some cases, are needed for other purposes such as irrigation; there is therefore a considerable human pressure on the fish stock which aggravates the climatic effect.

3.1 The Sahelian Zone

The Sahelian Zone covers a large part of three major basins, the Senegal River, the Niger River and the Lake Chad-Chari/Logone River complex. The estimated fish catch from the Sahelian part of these three systems together was 220 000 t in 1971. However, since 1962 there has been a progressive decline in precipitation over much of the region. The level of Lake Chad itself was progressively lowered, and the floods were below average in several years from 1968 onwards. Recruitment failed in

some years. For instance, the 1968 year class of *Citharinus citharus* was missing in the Senegal River, a failure traced to a very short food season /2/. The situation became most serious in 1972 and 1973 when for two years the floodplains of the Senegal River, the Central Delta of the Niger, and the Yaérés of the Logone River were left dry throughout the year. During that period the fish catch declined steadily as shown in Table 1 /3,4/.

In the Table, the figures from the Senegal River are estimated total catches, whereas those for the Niger are landings of smoked fish at the main landing point in the Central Delta (Mopti). In both areas the re-establishment of more normal conditions in 1974 and 1975 brought about an immediate improvement in the catch, although the fish populations have by no means returned to the predrought state up to the time of writing. Apart from the short-fall in catch, other effects were detected. The most notable of these concerned changes in growth, reproductive success and relative abundance in some species from the Niger River /5/.

Table 1

Trends in catch in Senegal River and the Central Delta of the Niger

River	1967	1968	1969	1970	1971	1972	1973	1974	1975
	thousands of tonnes								
Senegal	30	25	20	18	18	15	12	21	25
Niger	9.5	10.8	11.1	11.2	8.8	7.8	4.2	3.6	7.6

The situation in Lake Chad was more complex. Apart from the failure of the flood in the Yaérés, a floodplain which is essential to the breeding and feeding of the young of many of the fish species of the system, the lake itself began to shrink. From its high Chad level of 22 000 km² in 1962 it diminished in area to about 6 000 km² in 1973, mainly by the loss of its northern basin. This loss has never been recovered, and the lake remains in its small state even today. The isolation of the north basin was brought about by growth of weeds, which have prevented water from breaching the barrier across the centre of the lake. The results of these changes on the fishery are shown in Table 2, which summarizes the amount of dried fish passing from Lake Chad between 1969 and 1977.

The rapid rise in catch until 1973-74 was correlated with the diminution in area of the lake, the concentration of the fish therein making them easier to capture. Subsequently the catch has dropped as the stocks have become over-fished. Other phenomena have also been noted. There have been high natural fish kills due to unfavourable conditions in the lake, and the migratory species which previously made up the bulk of the fishery have almost disappeared, to be replaced by less-appreciated species that are more resistant to the new extreme physical and chemical conditions in the lake waters /6/. Should the alterations in the régime of Lake Chad discussed above remain permanent, then a new type of fish community will emerge adapted to the new conditions and some of the species from the old assemblage will inevitably be lost, at least in their pre-drought form.

Table 2

Dried fish passing control points leading from Lake Chad

Year	Total Dried Fish tonnes
1969-70	8 760
1970-71	11 939
1971-72	20 722
1972-73	28 535
1973-74	34 840
1974-75	26 862
1975-76	14 483
1976-77	13 422

3.2 East Africa

The changes in the level of Lake Chad are by no means unique. In East Africa, a rise in the level of Lake Victoria of over 1 m occurred in 1959-60. The new level has been maintained ever since. The availability of extensive favourable habitats at the margins of the lake, led to a rise in abundance of certain species of fish, but in subsequent years there appeared to be a return to pre-rise conditions. In some cases the change itself seemed to be more significant than the relatively stable stocks on each side. From a fisheries point of view, the rise in lake level of Mweru-wa-Ntipa, from 1962-1964, of 6 m was a significant event in Zambia, quadrupling the average commercial harvest. The lake has also a long history of variability, having been nearly dry in 1949-50 (with mass mortalities of fish, hippopotami and crocodiles). It dried up previously in 1931, 1918-19 and in 1895-96 insofar as recorded observations indicate. The present catch is some 15 per cent of the total fish catch of Zambia, hence an assessment of the probability of a return to lower levels is of considerable interest to the country.

Another case in the region noted for variations in level is Lake Chilwa, Malawi. The lake has a very low diversity of fish species, 13 species having been recorded, with only three of sufficient abundance to be of commercial interest. As in Lake Mweru-wa-Ntipa, such low diversity is evidently one result of the fluctuation in level, while the physiological tolerance to environmental changes of these species appears also to be high. Unlike Mweru-wa-Ntipa, Chilwa has no obligate predator (the important catfish Clarias has broad food habits) a factor which was to help recovery of the populations following a period of severe desiccation. However, from a development point of view, the important feature is the extreme fluctuation in harvest ranging from almost 10 000 t (40 per cent of catches, Malawi) at high water (1965) to 100 t at extreme low water (1968), when the lake dried up completely. At the latter

time, the fish move up into the feeder river or perhaps burrow in the mud, and recovery is remarkably fast, though by no means immediate, with return of the water. Acceleration of the recovery of the lake appears to be possible through stocking, though it is somewhat doubtful that the occasional restocking needed would indeed be economic. Many of the fishermen are migrants and, for the more permanent ones, fishing is a catch crop supplemented by farming and other activities.

4. Conclusions

It may be concluded that fluctuations in the catch of fish in most inland waters have been associated with climatic changes for many years. Indeed the various climatic manifestations appear as a major regulator of fish populations in all but the largest bodies of water. Furthermore, where a fish stock is under severe stress from other sources, such as overfishing or pollution, even slight variations in climate may have considerable impacts on the species composition of fish community and ultimately on its yield patterns.

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CLIMATIC VARIABILITY, MARINE RESOURCES AND
OFFSHORE DEVELOPMENT

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1. Introduction

The oceans, occupying more than double the land surface area of the earth, naturally affect the world's climate and weather. The sea, particularly the shallow continental shelf zones, are potential sources of supply of raw materials for a rapidly expanding world population. The harvesting of mineral wealth from the oceans is affected to a large extent by the climate and by weather. In turn, the operations involved in extracting minerals may conceivably, if carried out on a large enough scale, upset the balance of heat received and emitted and so affect the climate locally or regionally, or even, by some remotely possible triggering action change the world climate.

The search for offshore oil is already extending to polar areas, and the problems of navigation in ice-infested waters, which have been relevant to world trade for centuries, are becoming increasingly important. If adequate planning for world energy supplies is to be made twenty or more years ahead, it is desirable to know whether any significant change in the extent of ice-sheets is liable to occur so that optimum decisions may be made when several different strategic courses are possible. The increases in population and in individual wealth call for extensive increases in the number of ports and harbours and recreational facilities in the coastal zones, especially in what have until recently been remote, semi-explored regions where little study has been made of the extremes of climate or weather. In choosing where to carry out new developments, it is desirable to take advice from those who have gained experience in the already industrialized parts of the world and to take note of the best meteorological knowledge that can be applied.

Marine resources, apart from fisheries which are treated in a separate paper, can be taken to include offshore oil production, metallic nodules, rich brines, sediments on the sea bed and chemicals from sea water. The location and use of these marine resources are affected by the change in climate in two ways, which are at the extreme ends of the time scale. The formation of oil and rich sea-floor nodules, and the chemical constituents of sea-water, are the result of geological processes that have continued for hundreds of millions of years. From what has been learnt about the formation of these minerals, it is clear that each has its own particular set of environmental conditions which have been conducive to formation and concentration into

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what are today deposits which can be produced economically. On the other hand, the difficulties that beset the production engineer and the scientist who explore and extract the mineral wealth, are associated with wind and waves which are short term weather effects for which accurate forecasts are needed.

The climatic variations being described at this Conference are of importance both to the meteorologist who is continually trying to upgrade his ability to explain them and to the long-term needs of the explorer who understands past geological conditions through observations of what is happening today. A further more direct application of the mechanisms of change of variables such as temperature and wind-patterns is in the planning of offshore structures and coastal engineering works, which must be designed to stand for periods ranging from decades to centuries in spite of any changes of climate. In general, the geographical spread of mineral concentrations is world wide, and creates a wide range of climate in which operations such as those of the oil industry must be carried out. Techniques and people must both be adaptable to wide variations of climate. For purposes of planning, suitable knowledge of the likely fluctuations of climate is necessary. These climatic variations are considered by the oil industry at all times and in this sense are different from problems such as the El Niño which affects the fisheries industry in one particular region (off South America's west coast) over a spread of years.

2. Mineral formation

2.1 Oil

Petroleum is a mixture of hydrocarbons ranging from methane with one carbon atom per molecule to heavy bitumens where molecules with hundreds of atoms are present. It is formed by the decay of marine plants and animals in shallow water conditions of sediment deposition. It is probable that a warm climate is needed for the abundant marine life required to provide an economic accumulation of oil. The hydrocarbons separate from the heavier sea-water in which they were formed, and collect in folded strata of porous limestone or sandstone rock. The oil is trapped in the porous rock reservoir by a layer of impervious rock known in the industry as 'cap-rock'. Oil fields are small, of the order of tens of square kilometres in area, compared to the vast areas of several hundred thousand square kilometres of depositional sediment basins, such as the North Sea area of north-west Europe. The chance of finding an oil reservoir by drilling at random is therefore less than one in one thousand, and geological and geophysical measurements to define the sub-surface rock structure are needed in order to reduce the chances to economically-manageable limits of ten or twenty to one. The problem of locating prospective oil fields in offshore areas is more difficult than it is on land, since the surface geological evidence from rock outcrops, and from man-made and natural exposed sections is obscured by the presence of sea-water. Geophysics therefore forms the main discovery tool in offshore oil exploration, but a preliminary geological assessment, based partly on consideration of past geographical environments is essential. It is in this part of the exploration programme that a knowledge of climatic variation, and especially of the mechanisms that determine climatic change, are valuable to the oil geologist.

The North Sea provides a recent example of how past climates have affected the rock strata and have provided conditions suitable for the laying down of gas and oil deposits. During the past few hundred million years, when today's rock series were being formed, the climate was not only affected by world-wide changes, but the wind-pattern at the Earth's surface and the current distribution in the oceans were revolutionized by the lateral drifting of continents.

The gas that is found in the southern part of the North Sea was produced during the Carboniferous period (some 350 million years ago) in conjunction with coal, when freshwater swamps occupied most of the area between what is now western Germany and south-east England. The methane gas accumulated in a 300-metre thick layer of highly porous sandstone that was formed when the swamps were replaced by dry desert conditions in the early Permian period (270 million years). The rock strata were folded and thus provided suitable reservoirs for the gas during a period of Earth movements that formed mountains and depressions in the land surface. The sinking of the southern North Sea basin allowed salt water to enter from the ocean to the north and the hot climate caused rapid evaporation, so that thousands of feet of rock salt and other evaporites covered the gas-impregnated porous sandstone, and effectively sealed the gas in place. The opening to the north, between present-day Scotland and Scandinavia, gradually deepened, and was filled with sediment produced by the erosion of the high ground of north-west Europe. The shallow, warm seas were conducive to high biological productivity, and oil accumulated in various layers of porous rock. The oil fields are now 3 000-4 000 metres below the sea-bed, covered with sediment ranging from late Permian times to the boulder clay produced by the glacial epochs of the last one or two million years. During this period, the land that is now north-west Europe was moving from a tropical latitude to its present position. The Atlantic Ocean was being formed by the drifting apart of the American and European continents, and the Earth as a whole was changing from the warm climate of past geological periods to cooler times. The study of the rocks provides some of the evidence for past climates, but there is no doubt that a thorough understanding of the mechanisms of climate is a necessary adjunct to geological deduction in locating marine mineral resources.

2.2 Deep sea deposits

The drifting apart of continents, such as is taking place to form the Atlantic Ocean, has a direct consequence in the Red Sea in the production of potentially valuable deposits of minerally enriched brines and sediments. The Red Sea is similar to the mid-Atlantic rise in being an active zone where 'plates' of crustal rock are being forced apart by upward pushing of hot volcanic material. This heat has produced the mineral concentrations that are observed at the sea-bed, and an understanding of the processes that are in progress should make it possible to locate similar mineral-rich zones in other parts of the world.

Over a hundred years ago, oceanographers discovered vast deposits of manganese nodules on the floor of the deep oceans in many parts of the world. These nodules contain iron and manganese, which have been deposited from sea water in suitable conditions of water acidity and temperature; small quantities of nickel, copper

and cobalt have been added to the main deposit, and the nodules form a valuable source of these minerals. The latter will one day become very expensive when land-based concentrations are used. The formation of the nodules and particularly the variations of the valuable metallic constituents, depend on climatic conditions and for a better understanding of the depositional processes a continuing association of chemistry, geology and climatology is needed.

Other minerals that are extracted from the sea-bed include gravel, tin and diamonds whose location is near shore and is related to the adjacent geology on land and to the rivers that provide the alluvial deposits.

2.3 Minerals contained in sea water

The sea contains vast quantities of minerals, but few are extracted, on account of the extreme dilution in which they are present. At the present time, salt (sodium chloride), fresh water, magnesium, bromine and iodine are obtained commercially. The oceans have been thoroughly stirred in the course of geological time so that climatic changes have no effect on the average composition of sea water, although it is, of course, the climatic cycle of water circulation between land, sea and air, with the accompanying erosion of the land, that accounts for the mineral content of sea water. Although these other minerals do not require the detailed climatic knowledge that is so useful in oil exploration, their production may raise problems concerned with the weather and climate. If fresh water may truly be considered as a marine resource, some knowledge of trends in climatic variation may be important when de-salination plants for the production of fresh water are being planned.

3. Mineral production

3.1 Oil

It is probable that about one-quarter of the world's oil lies beneath the continental-shelf areas of the world, and during the last fifty years offshore oil production has developed rapidly. The problems of design and operation have necessitated a heavy reliance by the oil industry on weather information of all types. In the exploration stage, mobile offshore drilling units are employed to drill holes 3 000-6 000 metres into the sea bed. The design of these vessels must be such that they can behave as stable fixed platforms while drilling, and as safe, mobile craft when being moved from one location to the next. When an oil field has been discovered, the oil may be produced by drilling many wells from a single fixed structure. The structures must be strong enough to withstand the force of the wind and the surface waves of the sea in the extreme conditions that may be experienced in the proposed location of operations.

For the fundamental design criteria of offshore drilling vessels, the structural engineer calls for wave height and period, in particular the largest wave that may occur in a period of 50-100 years. The oil industry has followed and initiated much work in assessing the relative merits of various methods of extrapolation used in estimating 50 or 100 year waves. In the North Sea, different wave criteria were used by government supervisory bodies in Norway and Britain, and one aspect of international discussions of the climatic impact on various types of human

activity could usefully be an agreed set of figures in any particular area. The same need arises for standardization applied to wind speed maxima to be used in design.

The forecasting of waves on the sea surface from wind data was based on both visual and instrumental observations, mostly near shore. For the North Sea, such tables have been modified by the UK Institute of Geological Sciences, based on six months continuous wave measuring at sea. More recently the Norwegian government, the Dutch universities and the UK oil operators have produced separate North Sea wave models, which are being co-ordinated by the Oil Industry International Exploration & Production Forum (E & P Forum). The wave models enable past weather records to be used in calculations of the wave height, and so provide better extrapolations for the design engineer than is possible from the measurements at sea, which are of comparatively short duration. The UK Offshore Operators Association (UKOOA) has organized more than three years of continuous ship-borne wave and weather measurement in the northern part of the North Sea, where extensive drilling and production operations are in progress and have recently installed a large recording buoy to provide similar data in real time in the western approaches to the English Channel.

The pattern of waves is economically very important in the design of offshore structures, which must survive the continual impacts and pressures for 20 years or more. It would be disastrous to minimize the forces and endure structural failures. On the other hand, too great a factor of safety leads to cumbersome and expensive structures. Interest is being taken at the present time in the direction of wave patterns, as well as in the height and period of the waves, since it is realised that 5 per cent or more of the quantity of steel used can be saved by placing a suitably designed platform in the optimum direction. Since the offshore structures must remain for several decades, it is useful to be apprised of any trends in climate which may cause the weather to get better or worse. Old wind records can be used to give more reliable extrapolation, than extensions of observed data based on statistical methods; but it is essential that the wave-model be reliable. From the oil industry point of view some standardization amongst different nations, in particular where these nations are adjacent to common sea areas, is important when efforts are made to comply with design standards or guidance laid down by governments.

Offshore oil may exist in almost any continental shelf area of the world, and lessons may well be provided by North Sea experience to those who have to operate in other parts of the world. The North Sea work was preceded by extensive oil production in the Gulf of Mexico and in the Persian Gulf. In both instances, the weather was generally less severe than in the North Sea, since, although hurricanes occur a few times a year in the Gulf of Mexico, they cover a comparatively narrow damaging track and are not so harassing to the oil industry as is the almost continuous winter storm weather of the North Sea. In the Gulf of Mexico, many government recording stations provided a good backlog of climatic data on which design plans could be based. In the Persian Gulf, the weather is not so severe, and there is a limited fetch, so that very long waves do not occur; but there was very little past observation twenty years ago when operations started, and the oil companies have now collected a useful coverage of pressure, wind and temperature measurements at about thirty reporting stations. Engineering design in this rapidly developing area can now be based on a reasonable sample of weather conditions. The only way

to obtain such a sample of weather is to make the observations, and countries should be encouraged as early as possible to collect meteorological and oceanographical data.

Other climatic factors that affect offshore structures in addition to wind and waves are the currents in the sea, which scour foundations and cause movement of sand on the sea floor. Rainfall may be of marginal importance in some cases, but the effect of the sea water itself is probably the critical factor in corrosion and marine growth, both of which are liable to upset design calculations.

For several years, offshore oil prospects have been considered in areas where ice presents a problem. Drilling has taken place off the Labrador coast, off Greenland and in the southwest of Alaska in the Beaufort Sea and in the Canadian Arctic islands. Expert knowledge is needed in any particular area to tell the designer of drilling and production structures what is the ice-thickness, when the ice occurs, whether forecasts can be made of future ice behaviour and if possible the long-term trends. For example, observations are published at times which suggest that glaciers are receding and a warm period is approaching for the northern temperate zone. If such a trend could be accurately demonstrated, it would be of invaluable help, not only in deciding which is the best of several possible operating techniques, but also in planning reserve strength of structures for future severe conditions, or vice-versa. The Viking settlements which were established in Greenland around 1 000 years ago, when the northern hemisphere was enjoying warmer weather than today, were abandoned in the fourteenth century when the 'Little Ice Age' set in and it was impossible to sail to supply the colonists. Some years ago, the Arctic ice advanced on Iceland, and has subsequently receded. Are climatic variation studies well enough established to provide forecasts for several years ahead of how the ice-fronts will behave? Even if forecasts are only of a statistical nature, planning will be assisted if the behaviour of ice, together with fluctuations from the average, can be given, so that the mean length of the operating season over a period of years can be used in the economic assessment of the situation.

A considerable amount of work along these lines has been done by the Canadian Government Department of Fisheries and Environment in the course of their excellent Beaufort Sea project. This practical and theoretical investigation provides a fine example to governments of the world in collecting oceanographical and meteorological information of practical use not only to the oil industry but also to other potential users of Arctic areas. The Ice Climatology study is based upon such data as twenty years of observation of ice-sheet movement in the North Canadian Sea areas. A summary of these results shows that a useful approach can be made in predicting the length of the operating season of free, open water, from the weather pattern of the previous summer. The variation in the Beaufort Sea was quite large during the study period. In good years the ice-cover was less than 10 per cent of the surface by mid-June, whereas in bad years it was still 70 per cent in the middle of August. Freeze-up varied from 1st October to late October. The prediction of good years is made by examining the sea-level pressure distribution in early winter and by watching the resulting cyclonic circulation, which is reflected in the flow of ice from the Laptev Sea and the New Siberian Islands across the Pole and into the area north of Greenland. Part of this flow forms a continuation of the North American Gyre which may eventually bring old ice to the Beaufort Sea. The old ice, being thick, delays the clearing of the sea when the melting season starts. This technique would have predicted nine out of ten good years, two of the fairly good years and also five

out of six of the bad years. Hence the method will be of great value in forward planning of a drilling programme for the following years. Presumably, similar correlations may be found for other parts of the world, especially if knowledge of meteorological models in Arctic regions is developed in association with the increasing research into climatic variation.

Experience of ice conditions in the Cook Inlet of Alaska has led to the design of novel one-legged drilling and production platforms. To work in areas subject to seasonal ice, structural engineers require forward estimates of ice-thickness. New techniques based on radar or sonar may prove of value. Mathematical ways of calculating the worst ice conditions, on the lines of the 100-year wave, are also needed. Advice on what meteorological and oceanographic measurements are desirable will, it is hoped, be forthcoming as the underlying forces affecting climatic variations are understood.

Possible long term changes in climate must be considered when a choice is made between alternative methods of bringing offshore oil to the shore. For example, in the North Sea, small oilfields at a distance of about 100 miles from shore, producing less than 5 million tons a year, are probably most economically served by collection of oil by tankers at loading buoys stationed near the oil field. On the other hand, it pays to lay pipe-lines when the production rate is 20 million tons a year, as in British Petroleum's Forties Field. The weather, both as it inhibits loading at offshore terminals and as it increases the cost of pipe-laying, is a necessary part of the economic calculations.

Although short-term forecasting of wind and waves is not strictly part of what is normally accepted as climatic variation, the accuracy of forecasts does depend on a good understanding of the mechanisms of climate, and as forecasts for longer periods are always being requested by oil operators, the importance of climatic models will increase. In addition to design criteria, which are needed also when planning new ports and recreational shore facilities, the oil industry is dependent on accurate forecasts of weather to ensure safety during critical operations such as the moving of exploration drilling platforms from one location to another or the laying of sub-sea pipelines. The forecasts need to be very good for 12 hour periods and good for 24 and 48 hours, and it is hoped that the improvements that have been made in the past years will continue, so that reliable 3-day and 6-day forecasts may be available. In the Gulf of Mexico, the North Sea and the Persian Gulf, the oil industry has found that close personal liaison between the forecaster and the operations manager is essential for good working and in order to make the most of weather opportunities as they arise. Some government meteorological departments are providing oil company forecast services as well as collecting the basic data on which the forecasts are made, and one advantage of international discussion of the climatic impact on operations is to let meteorological offices throughout the world know the particular requirements of the oil industry, which differ, for example, from those of the air transport industry.

Wave forecasting was developed by Commander Suthons of the UK Royal Navy and by Professor Sverdrup at Scripps Institute of Oceanography. When offshore oil exploration began in the Gulf of Mexico, adequate knowledge was available to provide forecasts for long-term structural design and for day-to-day operations by specialized commercial organizations. In the Persian Gulf, it was necessary to provide the basic meteorological data before it was possible to make forecasts and oil companies in the Gulf area established some thirty reporting stations, some on land and some on offshore structures, which together with a suitable communication network have given twenty years good weather coverage. As a by-product the Oil Companies Weather

Co-ordination Scheme (OCWCS) has produced several publications describing the conditions in the Gulf, and is hoping that the newly formed regional seas convention will rapidly take over the processing of the twenty years of accumulated wind speed, pressure and temperature data.

When North Sea offshore oil operations started, there was a good network of government reporting stations all round the area, and as drilling and production proceeded, many platforms provided regular readings to improve forecasts by covering the middle of the region. In the deeper waters off the North Sea, when semi-submersible platforms are used, forecasting is made more difficult by the need to advise drillers when to pull the riser pipe out from the bore-hole in case of storm damage. It is necessary to wait until the weather becomes very calm before it is possible to re-enter the bore-hole, so that false alarm forecasts of storm weather can lead to long, unnecessary delays. On the other hand, a bad storm could cause the rig to drag its anchors and damage the drill string and the sea-bed fittings to the bore-hole. A similar circumstance occurs during pipe-laying, when severe weather makes it imperative to disconnect the pipe-laying barge from the pipe, an operation which again causes delay in re-starting the pipe-laying process.

Weather forecasts are desirable for operating supply boats, and the 12 to 24 hours forecasts which are normally sufficient for critical operations such as moving drilling rigs or pulling out drill-pipe, need to be extended to several days when the distance from base to platform is over 100 miles. Some of the models being produced by national meteorological offices show promise of achieving long-term predictions. These may lead to a considerable saving in areas where rough weather is prevalent such as the North Sea, and may make it possible to pick out ahead of time the few days of calm 'weather windows', and thus avoid the cost of keeping expensive equipment such as floating cranes on station for weeks without doing any useful work. In this respect, forecasts of good seasons a year ahead, as appears to be possible with Arctic ice, may be of great help in planning movement of the giant offshore structures that are being used for fixed production platforms. In all cases of forecasting for critical operations it is necessary for the design engineers to assess the vulnerability of their structures to wave forces and to give the forecaster the average and maximum wave height which can be tolerated with safety.

Some drilling has taken place during the past few years off the east coast of Canada, where there is a hazard from icebergs floating down from glaciers in Greenland. It is possible to nudge these menaces off collision course with offshore structures, and any assistance from long-term forecasts of the probable frequency of icebergs will assist in planning stand-by tugs, etc. Short-term forecasts of potential ice formation and movement will be valuable in all offshore Arctic and Antarctic operations, and the industry needs advice on what parameters to measure at regular intervals to assist in this work.

The use of recently developed technical aids such as observation from satellites and by radar and the processing of data by computer is employed in oil industry offshore work when these methods can provide useful supplementary information. An essential part of the forecast system is the method of communication which must be

such that information is sent to operating bases with as little delay as possible. There is a fear that the modern trend towards centralization of information may make it difficult to obtain data where it is required in time for operational use. Direct links, especially with local reporting stations, could be important in providing rapid information rather than waiting for the same information to be broadcast hours later after compilation by a central collective. An allied concern is with the security of data. Traditionally, civil meteorological and oceanographic data have been exchanged with the minimum of security cover and at no cost, and this has been essential to the development of adequate forecast services. There has been a tendency lately to regard collected data as being saleable amongst offshore users. Some data may reflect company interests or actions, but generally routine observations do not fall into this category and free exchange of data should be required without restriction or added cost. This particular problem may require more pressure from users, more co-ordination by government agencies and probably the injection of official funds in order to insure that, as with the Beaufort Sea example provided by the Canadian Government, the best information needed for safety and environmental considerations, together with rapid development of national mineral resources, is forthcoming.

3.2 Other minerals

No-one has yet embarked on a regular production system for recovery of manganese nodules or of hot brines from the sea-bed, but it is possible that several groups will attempt this in the near future. Some delay is being caused by the lack of agreement at the Law of the Sea Conference concerning the ownership and national or international status of this type of mineral wealth. It is probable that some of the experimental work that has been proceeding for many years will soon reach such a stage that commercial operations will be practicable. It is possible that the deep ocean more than 200 miles from shore could be placed under international control, or it could remain, as it is now, as high seas belonging to nobody. The technical systems will probably require weather reports to provide forecasts of when to suspend operations. Since the scenes of operations will generally be hundreds of miles from land, reliance will have to be placed on reports from neighbouring ships, and more particularly from satellites. Warning reports of impending swell and storm waves may be provided by suitably placed buoys, and the experience of buoy operation in the GARP experiments should prove invaluable for future deep-sea mineral operations.

3.3 Chemicals from sea water

The plants that have been operated in the past for magnesium and bromine have been essentially shore establishments. From a climate and weather point of view they are subject to the same considerations as apply to ports and oil terminals (see section 4). Oceanographic knowledge of coastal water movements is needed to ensure a continuous supply of undiluted sea-water, and the effect of effluents on local climate may have to be taken into account. In this respect, the problem is like that posed by hot water effluents from thermal and nuclear generating stations.

4. Ports and oil terminals

The population of the world is increasing and is becoming accustomed to more man-produced equipment, both for improvement of living standards and to provide recreation. Transport is becoming more commonplace, and there is a consequent increase in

trade and tourism in nearly every country of the world. One result of this recent activity is the extensive development of the coastal zones in areas that had previously only been sparsely inhabited.

New ports, oil terminals and recreation beaches are rapidly growing in places where little in the way of topographical or oceanographic survey or in meteorological and oceanographic measurements have been made. Although much of the information needed to plan this type of development is concerned with currents and movements of beach material, climatic considerations are most important. This is especially so, when it is remembered that, while oil installations may be required only for a few tens of years, ports and harbours tend to be used for centuries, and any long-term trends in climate may be of vital importance in a design that is to be adequate for the future.

One of the most active regions of the world at the present time is the Persian Gulf where there are many new oil installations of various types for exporting crude oil. As a consequence of the profit made from the oil, many new harbours are needed to import merchandise from industrialized countries and equipment to develop roads, housing and new manufacturing industry. Fortunately, in this area, as was noted in the discussion on weather forecasting, there are now available twenty years of good meteorological data. Although only a portion of this material has been worked up in a critical form able to be used by design engineers, the analysis is being carried out by the oil company group who have collected the data. For such places as Kharg Island, where some years ago a tanker loading terminal was built, the results have been used to guide the choice of site. It is important, when catering for the very large crude carriers that are used today, to site the loading jetties so that the prevailing winds assist rather than hinder tankers coming alongside in order to load. In the early days of reporting weather data, the OCWCS group was interested mainly in providing forecasts for purposes of critical movements of mobile offshore drilling units, and the tanker side of the oil business co-operated fully in providing this information from their existing loading points. Now that a lengthy period of data collection has been achieved, the designers of terminals and harbours are reaping the benefit of their early co-operation. Since many non-oil coastal works are now in progress or are being planned for the future, it is probably an opportune moment to speed the working up of the twenty years of data to make it available to all construction engineers and consultants. The opportunity exists now that a technical plan is being developed for the Regional Marine Meteorological Programme and also in view of the fact that a Convention has been agreed for the Protection and Development of the Marine Environment and the Coastal Areas of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates. Since the movement of oil slicks on the sea surface is mainly controlled by the wind, the weather data over as long a time as possible will be needed in order to calculate the probable ultimate landing place of oil that persists long enough to reach a beach. The action plan of the environmental programmes has already been agreed with a budget of US \$ 6 320 000 for the next two and a half years and one of the most useful tasks that could be undertaken, without any delay since all the records are available and people to process them can be found by the consultant firm which holds the data, will be to finish the analysis and thus provide basic information needed for other work and at the same time demonstrate the activity and efficiency of the new organization.

It is only in the exceptional coastal regions of developing countries that data as comprehensive as that in the Persian Gulf are available. All efforts should be made for newly established meteorological offices to establish reporting points so that some idea of climatic parameters can be built up. This work will be assisted by observations from satellites and by co-operation through the World Meteorological Organization. For the purposes of holiday beaches, consideration of beach pollution and of coastal protection, information is needed of the prevailing wave direction and size at various seasons. In places where only a few years' measurements are available, help may be provided by improved climatic models and by analogy with areas of similar geographical situation.

The importance of accurate forecasts of wave-height in the offshore construction industry has been known for a long time. In regard to some modern breakwater failures, Minikin has noted that the damaged structures had been designed to resist a wave height less than that which brought about their destruction. Cases in point are Algiers, Catania and Antofagasta. In each of these cases, a height of 6 m (20ft) was decided to be the maximum height of storm waves, but, in each case, failure was brought about by waves of 9 m (30ft). History repeats itself in that an experimental structure recently erected for the express purpose of measuring wave forces, collapsed in the first rough weather at the site.

5. Sea transport

For some years, ships have been routed across the Pacific Ocean, with the help of forward weather forecasts. The objectives are to save time and to avoid discomfort and ship damage by selecting a course around rather than through areas of severe storms. The technique has proved successful both to the satisfaction of captains of US Navy supply ships and more recently in saving money for commercial ship owners. It is clear that both short-term forecasting and long-term planning are involved in this type of work. In addition to avoiding local storms, seasonal changes may favour one particular route rather than an alternative, and in the longer term even changes in terminal points of the voyages may be advisable. For the latter, an understanding of the underlying forces that determine variation of climate is valuable, even if only to give guidance of a statistical nature of the preference for one route over another.

One particular aspect of ship routing which is becoming of increasing importance is concerned with voyages through ice-infested waters. It is here that trends in climate variation can influence planning decisions many years ahead, and also where long term forecasts can allow great saving by arranging ship passages at the optimum seasons. It is of course possible to tackle the ice problem in a direct manner by using large modern ice breakers and strengthened ships as demonstrated by the USSR in their epic voyage through the Arctic ice to the North Pole. However, this does not mean that advantage should not be taken of climatic knowledge when planning operations in Arctic areas.

One example of looking ahead at ice conditions has recently been reported by the US Geological Survey. The Columbia glacier, on the southern coast of Alaska, has an area of over 100 km², and discharges its burden of ice and water into Prince William Sound, which is 40 km to the west of the Trans-Alaska pipeline terminal at Port Valdez.

Research has been started to determine whether the glacier is advancing or receding. If, as a result of changing climate there is a significant advance, a volume of 200 km³ of ice might be deposited in the sea over a period of about 40 years, forming a potential hazard to tankers plying between Port Valdez and the American west coast. Coastguards admit that the danger is serious and various contingency plans to keep the icebergs out of the shipping lanes, on the lines of the measures that have been taken in the past in offshore drilling off the Laborador coast, have been initiated. The instability of glaciers under certain climatic conditions and at certain stages in the life of the glaciers is well known and can lead to the discharge of abnormally large quantities of ice in a short time. Unfortunately, when the Alaskan pipeline was originally planned, the understanding of glacial behaviour was not as good as it is now. In particular, climatic conditions in which glaciers begin a drastic retreat, are preceded by a thinning of the ice and such thinning has been observed on the Columbia glacier. This is the only Alaskan coastal glacier that has not experienced a retreat in the past thousand years, and this could be due to a rise in the land surface which is holding back the front edge of the ice flow. It will help the regular operation of Port Valdez and the export of crude oil if the long term climatic changes and the details of glacial behaviour in the area are better understood, so that they can be forecast with the help of better measurements by strain gauges, new airborne sensing devices, etc.

The Arctic Ocean may become as important as southern Alaska for the oil industry. The discovery at Prudhoe Bay and the exploration activity in the Beaufort Sea and in the North Canadian islands and in Siberia indicate that the land surrounding the Arctic Ocean could be one of the world's large oil producing areas. For offshore work, and for transporting oil, improved navigation of Arctic waters will be needed. The USS Manhattan experiment some years ago demonstrated the possibility of large tankers using the historical Canadian North West passage, and tankers may be a better solution than pipe lines in the Hudson Bay region. The increased knowledge of ice movement which is made possible by observation from satellites leads some meteorologists to forecast that in five years time a sufficient advance will have been made in understanding ice movement in the Arctic and its correlation with measured weather pattern to produce a large computer model of the ice drift both in relevant regions and for the Arctic as a whole.

In the meantime, experiments in moving ships through the ice, and in the use of available satellite and weather observations to select the optimum routes, are being made by the US, Canada and the USSR. More powerful ice-breakers and more strongly constructed freighters and tankers could possibly run a regular service from Murmansk to the Bering Straits. Just as the trans-polar route saves distance for the airlines, so the direct sea voyage would save 1 300 km on a single journey. The use of hovercraft to precede the ships is being tried as a method of making the ice sheets break more easily. Each technical advance will call for specialized information, such as age, thickness and past history of ice, in order to take advantage of the new developments. The voyage of the Russian vessel Arktika to the North Pole has demonstrated that the polar route is feasible. It remains to be seen how many months a year this course can be followed to determine the economic viability of the project and incidentally, if oil is to be transported, to assess the costs. Movement through the ice will probably be slower than through the open sea, and it may be economically advisable to travel the conventional route. For the supply of materials for oil and

gas development, there is, however, no choice, and both ice-breaker and ship development, together with better meteorological and oceanographic data, will be needed in the next few decades. The development of the Prudhoe Bay oil field in North Alaska was carried out with heavy freight brought in through the Bering Strait during a very restricted summer period. Even with the ships then available it was economically better than an overland route.

The Great Lakes of Canada and the USA provide an excellent example of the use of climate knowledge for inland water navigation. The US Coast Guard has been providing ice breaking services on the Great Lakes to meet the needs of commerce at least since World War II. Winter ice usually exceeds 90 per cent cover on Lake Erie, while Lake Superior, which is further north, is often less than 60 per cent ice covered during a normal winter. It is obvious that factors such as depth of the lakes, input from rivers that feed the lakes and actions of currents, winds, waves, etc., will affect the large ice floes that infest the waters. The usual work of collecting information of extent of seasonal ice-cover and the local weather pattern is being carried out by a combined operation funded by the riparian nations. It is hoped that this type of work will be followed by countries in all other parts of the world so that, firstly, a lead can be given by the good work being done by industrial countries, and secondly, the rest of the world will appreciate the value of the collection of weather information as soon as possible, so that when the need arises for the information, an adequate supporting back-log of data will be available.

Some of the schemes being considered in addition to the actual ice-breaking entail the use of air bubbleurs to stop ice formation by circulating warm bottom water and the use of booms which will deflect the ice-flow and protect the navigable channel. The strategic placing of nuclear power plants could assist in keeping the passage open by virtue of their warm water effluent. In planning for and deciding on the relative merits of these expensive projects a forward prognostication of climate trends is invaluable. There are conflicting interests between navigation and water intake for power plants which call for climate and weather information and increased knowledge of ice formation. For example, if heat from power stations is used to combat ice, it must either be controlled so as to permit forming of an ice cover upstream of hydro-electric plants or else must be massive enough to stop formation of 'frazil' ice, which is damaging to hydro-plants. A report on the Lake Michigan ice cover in 1976-77, which was one of the four coldest winters in the past 80 years, demonstrates how any planning for navigation or plant sites must be based on the extremes of ice variation that can occur. It is interesting to note that extensive ice cover develops on Lake Michigan only when the southern sub-region of the lake experiences a severe winter. Improvements in the use of radar methods for measuring ice type and thickness from aircraft will allow more of this type of correlation to be established and will help in day-to-day and seasonal operations.

6. Climate and oil spills

6.1 General effects

The total production of oil in the world is around 2 500 - 3 000 million tons, equivalent to a volume of 4 to 5 cubic kms (about 1 cubic mile). The volume of the oceans is 360 million cubic miles (1 400 million cu. kms) so that provided sufficient mixing takes place, the small percentage of oil that is spilt (0.1 per cent) becomes sufficiently diluted for it to get lost by natural processes. Since oil is

formed in a marine environment from the decay of animal and plant matter, there are always hydrocarbons of a petroleum-like nature associated with recent sediments on the sea-bed, and there do not appear to be any animal or plant chains of life that concentrate hydrocarbons as is the case in some instances with heavy metals. However, oil normally floats on water, and it is possible that the average albedo of the earth could be significantly altered if a large proportion of the sea or ice of the world were covered with a thin film of oil.

The area of the seas is 370 million km² so that the total annual production of oil would be needed to produce a 1 mm cover of the oceans. With an annual output to the sea of a few million tons, including tanker accidents, land-based effluents, tank washings, blow-outs and natural seepages, only a fraction of the sea surface will be covered to a thickness that forms a black patch which might increase the heat absorbed from the sun. Thinner films, such as the slicks which are the only sign of many oil spills, cover large local areas but are very short lived. The experiments made by government research departments such as the UK Warren Springs Laboratory indicate that in the North Sea, 10-20 per cent of oil at the surface is mixed with the underlying water each 24 hours. The experience of blow-outs such as that in Norwegian waters a few years ago demonstrates that the oil slick disappears entirely in rough weather after a few days. The total oil pollution to the sea per year is therefore not the right figure to take when considering changes to the reflecting power of the sea, but rather the average spill for a few days or one hundred thousandth of the annual production. It is possible that more persistent oil slicks may obtain in ice bound regions, and these will be considered later in the light of experiments made in the Arctic Beaufort Sea.

There has been a suggestion, based on observations, that oil slicks at the sea surface may cause an enrichment of heavy metals, etc., and that these may be deleterious to animal and plant life. However, there is no obvious link here with the albedo of the oceans. The oil slick, during its short existence, does form a smoother than normal sea surface, since it exerts a restraining force on minute ripples, and hence presumably provides a less undulating surface on which wind forces can operate. The old seaman's employment of 'oil on troubled waters' was probably an application of this principle, and served to smooth the short-period waves which are hazardous to small boat operations. It is possible that a significant albedo increase would be produced by material associated with animal and plant growth, but in the prevailing conditions of rough water in the open ocean it is unlikely that an effect persistent enough to affect the annual heat budget would ever occur. However, it is worthwhile taking note of the various possibilities and making suitable calculations as new information becomes available. Although it is difficult at this time to assess the effects of surface films quantitatively, the increasing number of sources of petroleum discharges and the possible importance of the chemistry of the films calls for close observation.

6.2 Offshore oil production

The contribution from offshore oil production operations is about 60 000 tons a year, which is only 1-2 per cent of the total oil spill from other sources. The figure for oil introduced into the sea from natural seepages is possibly greater than from other causes and is often underestimated because only those seepages close to the

shore have been identified. In cases where seepages have existed throughout historical times, there is no observable effect on the fauna and flora. Oil spills in the sea are probably more a nuisance value to human beings than a harmful agent to other animals or to the climate.

Evidence concerning the limited environmental effect of oil operations has been provided by a recent comprehensive study by the Gulf Universities Research Consortium. The objective of the study, known as the Offshore Ecology Investigation or OEI, was to determine the effect of petroleum operations in the "Louisiana Oil Patch", the continental shelf area that has experienced about 25 years of intensive petroleum exploration and production operations. If, indeed, exploration and production operations have an adverse effect on the ecosystem, here is where one might expect to find the evidence of such effects. This is particularly true with regard to long range effects, which might be hidden by natural phenomena over the short term. The study indicated the following:

- (a) Natural phenomena completely dominate the characteristics, productivity and general health of the ecosystem. These include seasonal changes in water quality, water mass movement, and the turbid layer arising from the Mississippi River which contributes far more to silting and sedimentation than does production and drilling activity.
- (b) The presence of offshore producing platforms and pipelines have an insignificant effect, which, if anything, appears beneficial, due to the reef effect of the structures increasing the productivity of basic nutrients in the vicinity.
- (c) Petroleum operations have not resulted in any significant accumulation of potentially toxic materials in either the sediment or water column in the vicinity of such operations.
- (d) No accumulation of hydrocarbons was found in the animal life in the area and the accumulation of organic materials in the sediments and beach sand was found to be of a low order and not ecologically significant.

The report also emphasised that insofar as environmental protection is concerned, there was little comparison between the exploration and production operations of the late 40's and 50's in shallow waters (which would presumably be more susceptible to ecological damage) and operations today with advanced technology in deeper waters more remote from the coast.

6.3 The SLIKTRAK computer programme

During discussions on civil liability, it became apparent that there was a need to illustrate effectively and realistically the combined effects of clean-up activities and natural spill-reducing phenomena, and so predict the quantities of oil that could reach the shore. Estimates have been made of the amount of oil that might be emitted in a platform blow-out and the duration of the emission before the wells were brought under control. The known rate of evaporation from the surface

film of oil and estimated amounts of oil that could be contained and picked up by booms, skimmers, etc., were fed into the analysis. The movement of the oil slicks is determined by the wind speed and for this purpose the computer selected random weather from determined meteorological data over the past three years. The weather conditions which, if severe, could hamper containment operations, would increase the loss of oil slick by natural mixing with the sea water. The removal of oil from the surface in this way was included in the programme based on rates of mixing determined by the UK Government research station at Warren Springs.

The cost of breaking up oil slicks with dispersant was included in the cost of the operation, and the remaining slicks, driven mainly by the wind, were followed until they disappeared completely or reached the shore. The effect of currents was included, but is very small compared with the wind effect in the North Sea, especially as most North Sea water movement is due to tidal streams and reverses with the tidal cycle. The computer assessed the cost to fishermen of temporary loss of livelihood, to hotel and boarding house keepers of diminishing tourist trade and to the local authorities and government for cleaning beaches. Five thousand random incidents were analysed by the computer on this basis. The simulation showed that the average total spill cost is expected to be \$6 million, that the probability is 90 per cent that the spill cost will not exceed \$15.8 million and that the worst case would amount to less than \$25 million in civil liability.

Although the SLIKTRAK programme is designed for random accidents to production wells in the North Sea sector, it can be readily adapted to other areas, and with small modification to replaying real incidents with actual weather data. The recent Ekofisk Bravo incident in the North Sea, where the total oil spilt was less than a quarter of the Torrey Canyon spills, and where the point of spill was more than 100 miles from shore, shows that the SLIKTRAK prognostications are on the right lines and if anything overrate the civil liability costs. The Bravo spill was, like accidents in the airline industry, due to a combination of human errors and fallibilities, and was put right by the opposite facet of human abilities, bravery, ingenuity and experience in adversity.

The computer programme provides not only a useful yardstick for legislation in other parts of the world, where extensive offshore oil production may develop but also shows on what beaches spills are likely to arrive, and the size of the clean-up problem that may be posed. It is probable that more experimental figures for evaporation and mixing of oil with water will be required for different climates, but, provided the meteorological data are available, the general lines of thought of the SLIKTRAK programme are applicable.

6.4 Ice-bound areas

Considerable thought has been given by the Canadian Department of Fisheries and Environment to the effect of oil spill during oil exploration and production operations in the Beaufort Sea. This work extends the thinking underlying the SLIKTRAK programme. Because of the short summer drilling season, it is probable that no relief well could be drilled for more than a year, and so the blow-out may last longer than in, say, the North Sea. If oil is discovered in the Arctic, the intensive,

development in the area will increase the possibility of oil spills, and the special conditions may call for exceptional clean-up and containment treatment.

The movement from an oil slick will be controlled by wind forces as in the SLIKTRAK model, but will be modified by the ice. Oil could be driven under an ice pack and carried considerable distances before being released. It is expected that much thicker oil films will be produced in the presence of ice than in the open sea. The spreading of oil on the ice surface is usually retarded by snow cover and since the albedo of oiled snow is about one-third that of clean white snow, melting will be accelerated. The oil tends to form pools in depressions in the melting snow. An expected blow-out in the Beaufort Sea exploration area could contaminate 7 700 km² of ice. However, "the amount of weathered oil which would be dispersed from a single well blow-out running wild for a year would be unlikely to have any effect whatsoever on global or even local climate. While it is certain that oiled ice will melt much faster than clean ice, natural fluctuations in the yearly ice-cover would mask the extremely small changes which would be caused by oil in the volumes assumed" (Tech. Report No. 39 - Beaufort Sea Project, Department of the Environment, 1230 Government Street, Victoria, B.C.). Even if the blow-out ran for several years, expert opinion does not believe that there will be an observable effect on climate, although there may be substantial environmental and social impacts.

7. Conclusions

The report provides a survey of the activities that are being carried out in marine resource development and in the construction of ports, harbours and other coastal facilities, and ship routeing in difficult climatic situations. The impact of climatic variations is often more important at the short-term weather forecasting end of the subject, but extremes of climate and long term trends are important if catastrophes on the one hand and gross overdesign on the other are to be avoided.

Oil is the most important marine resource at the present time, and is likely to remain so for the next few decades. Manganese nodules and similar sea bed mineral concentrations may be valuable in the future when economic extraction methods are devised and when the price of metals increases as a result of exhaustion of readily exploited land deposits.

Experience shows that, although the developments are in the forefront of engineering knowledge, adequate techniques and structures have been produced to service the offshore oil industry. The industry has necessarily become well aware of the importance of weather forecasting when performing critical operations at sea and of long term sea-state information in the design of offshore platforms, drilling rigs and loading terminals. The North Sea has provided an impetus for fresh effort in improving models for wave forecasting so that old climatological records may be used to extend the time span to enable 100 year design waves to be calculated more accurately.

In addition to moving into rougher and deeper water, the oil industry is operating in Greenland and the Arctic, and the oceanographic and meteorological problems associated with ice are of paramount interest. Any climatic variation which can be reliably predicted will allow correct decisions to be taken in selecting the best among alternative courses of operation and construction.

The increase in population and in standards of living world-wide is leading to growth of coastal activity in areas where the meteorological information needed for engineering design is lacking. A better understanding of the climatic differences and similarities in various parts of the world will help in filling some of the gaps in knowledge by comparison with analogous situations.

The routing of ships to avoid bad weather and the improvement of ship design to minimize accidents are a continuing interest of industry. Navigation in ice-bound waters is attracting great interest both on account of supplying oil equipment in Arctic areas and of the desire to increase inland waterway use in continental areas such as the USSR, the USA and Canada. It is opportune that new sensors for use in satellites and aircraft are available at a time when overall views of such phenomena as ice movement are most needed.

There is a natural concern that pollution of the sea during offshore mineral production will in the long run affect the climate. Thin films of oil may well alter the albedo of the sea surface, but fortunately such films are short lived since the hydrocarbons rapidly mix with the upper layers of the sea water, as demonstrated by the short duration of oil slicks from oil well blow-outs. Fears that oil spills in polar regions will provide long term changes due to extensive melting of ice are, according to expert opinion, not well founded, and it is unlikely that oil production in Arctic waters will have even a regional effect on climate in an area where the annual variation of such parameters as onset of ice is very great.

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CLIMATE AND ECONOMIC ACTIVITY

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1. Introduction and Summary

Man's fundamental dependence on climatic variation is well understood by every human being. His ability to live in extremely different atmospheric environments is perhaps one of the striking characteristics distinguishing man from other animals. As Edholm (1966) has pointed out, man without clothing, heat, shelter and specifically cultivated food supplies, would be highly restricted to a very few world climatic zones. The pattern of human settlements, location and intensity of agriculture and industry, mental and physical health, vigour of the economy, and even distinct social pursuits among cultures, are partially the result of climate and its variability. Natural adaptive mechanisms such as body size, shape, and skin pigmentation have played vital roles. But man through learning and bringing together various combinations of resources such as clothing, design of structures, and energy conversion processes, has been able to ameliorate the effects of climatic variation in both geographical and time (seasonal, cyclical) dimensions.

Until several decades ago, man's image of the climate was one of an almost immutable force. That is, no human activity could possibly influence the climate or its natural variation, with the possible exception of air pollution episodes around large human settlements. Quite rapidly, this image has been altered. With steadily rising populations, energy-intensive economies, and new technologies, it is now recognized that man may not only have a significant influence on localized climate but also on regional and global climatic patterns 1, 2, 3. This potential dependence and feedback is depicted in Figure 1.

It is the central purpose of this paper to review and summarize the rather meagre evidence on the impact of climatic changes on various economic sectors of some nations. The discussion is not meant to be exhaustive by country or sector, but suggestive of the magnitude of economic impacts and potential dependence of various economic sectors on climate. It is reported, for example, that the economic cost to the United States of a 1 deg C reduction in average temperature may be as much as seven billion U.S. dollars per year when one examines about 60 per cent of the economy 3. However, this estimate only contains costs for urban, agricultural and forest sectors. It does not consider the implied regional modifications in agriculture, industrial siting, and perhaps city location. In addition, it does not include indirect effects

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on the United States from similar climatic change occurring elsewhere. For example, a simultaneous cooling effect in other nations will substantially alter how efficient the United States is relative to other nations in growing various agricultural crops. A global cooling effect may increase the U.S. efficiency in growing wheat and rice and reduce its efficiency in oranges, vegetable crops, and certain fruits relative to other nations. A general cooling effect is likely to increase global space heating needs but reduce air conditioning needs. Whether this impact, for any individual nation, will be economically positive or negative cannot now be determined, since complete economic analyses have not been completed. However, from a distributional sense, wealthier nations with widespread air conditioning already installed are likely to be better off than poorer nations with fewer space cooling systems to offset the increased cost of heating. In consequence, while isolated effects of climatic change on individual nations can be approximately assessed, the effect of global climatic variation on efficiency and distribution of costs among nations can only be vaguely perceived. In this paper, an attempt is made to examine qualitatively some of the more obvious international repercussions of climatic variation.

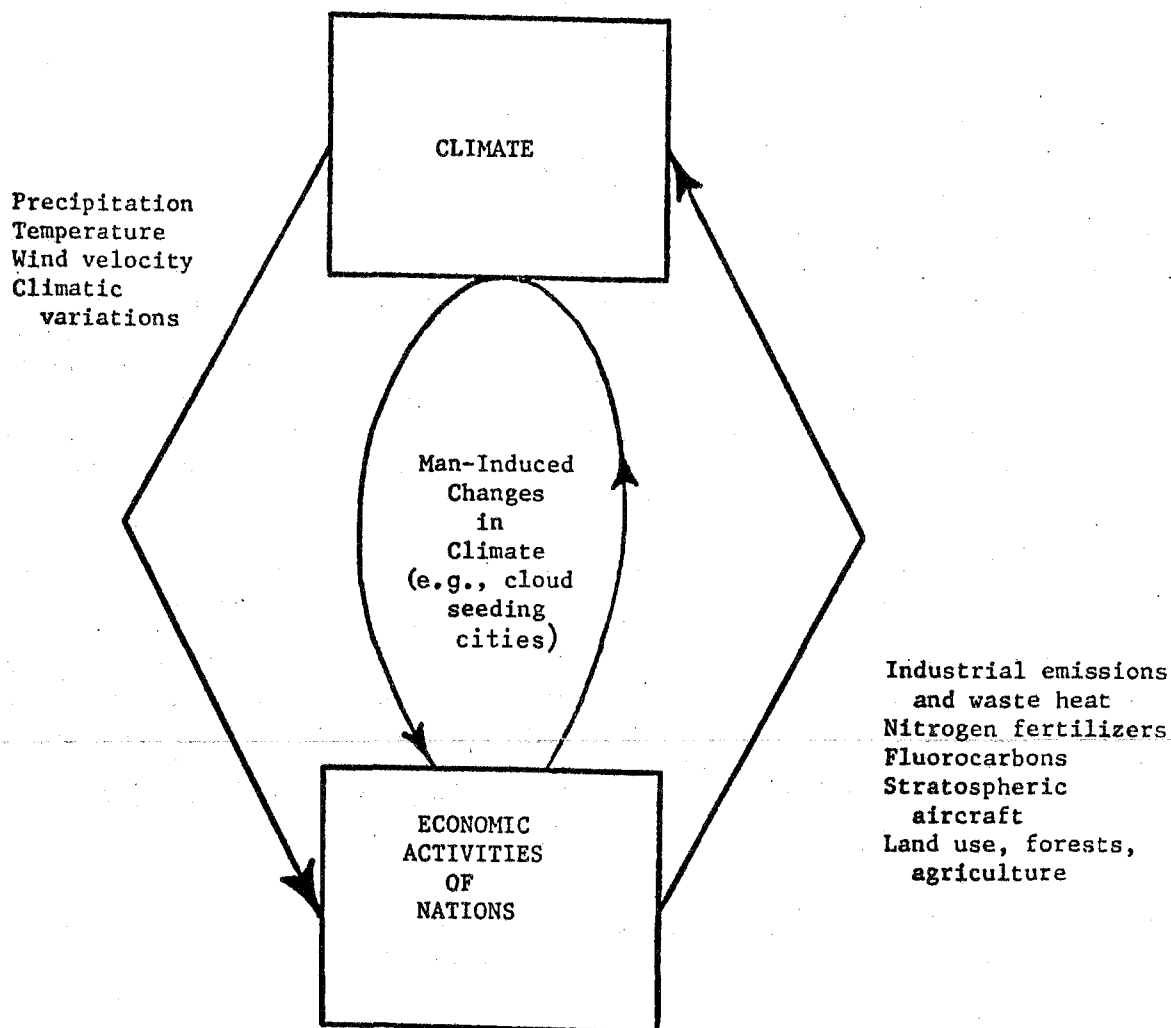


Figure 1. Simple Schematic of the Effects of Economic Activity on Climate and the Resultant Feedback on Economies.

If human activity through industrial or technological processes can substantially alter climate, what will it cost not to influence it adversely? With the exception of some rather crude estimates of control costs for emissions by stratospheric aircraft and from fluorocarbon production in the developed nations, little is known as to the magnitude of these costs. To control CO₂ would probably require very substantial shifts in energy conversion processes and perhaps changes in global reforestation policies. To remove the potential effect of nitrogen fertilizers on stratospheric ozone, by removal or reduction of their use, would almost be prohibitively expensive for the agricultural sectors of most nations 4.

While direct scientific evidence of global climatic change induced by emission of CO₂, NO_x and other by-products of industrial activities is not yet obtainable, there appears to be sufficient indirect evidence through experiments and historical observation to suggest that these emissions could significantly alter world climate. It has been proposed that the net effect in 50 to 200 years may be a global warming of several deg C with perhaps greater rainfall. However, the possibility of a net cooling effect when all potential stratospheric pollutants are considered cannot be ruled out. It is also the purpose of this paper to examine the potential economic costs and benefits of man-induced and natural global climatic changes over the next 50 to 100 years.

The stratospheric pollution problem from an economic perspective differs little from other types of pollution problems. The stratosphere, being a common property resource utilized by all nations but owned by none, is likely to be inefficiently managed as a sink for pollutants. To achieve economic efficiency, stratospheric emissions need to be regulated and, in simple economic terms, emissions controlled to the point where global marginal costs of regulation equal global marginal damages associated with remaining emissions. However, this simple rule cannot be applied for a number of reasons. To apply it accurately requires four well-defined empirically verified relationships: (1) a complete and concise damage estimate relating global damages to atmospheric changes for various rates and types of pollutant emissions; (2) relationships between costs of pollutant control and regulation, and rates of pollutant emissions; (3) empirically valid relationships between rates of pollutant emissions and atmospheric effects; and (4) knowledge of how various types of stratospheric pollutants interact and how this interdependence influences tropospheric climate. The central problem for stratospheric regulation is that none of these relationships is known with a high degree of certainty in terms of either sign or magnitude. Estimates to date on the third relationship suggest sufficient aircraft emissions will tend to reduce stratospheric ozone and thereby alter global temperature patterns. Best estimates to date indicate that on balance a global cooling and reduction in ozone will be costly to society, while a slight global heating may be economically beneficial or harmful 5, 6.

The direct cost of regulating some pollutants, such as SO_x, have been estimated with some degree of precision, while for others including NO_x, suggested methods of control embody redesign of jet engine combustion where accurate estimates of actual costs are not now obtainable. Thus, control costs are likely to be highly uncertain depending on the set of existing technologies, most of which were developed without cognizance of stratospheric pollution problems.

Given the inherent uncertainties and possibilities for large errors in measurement, how should the stratospheric pollution problem be analysed from an economic perspective? First, one might characterize the major distinguishing attributes for the upper atmosphere as follows:

- (a) There are large uncertainties (both in sign and magnitude) in the climatic effects of various levels of emission into the stratosphere, of oxides of nitrogen, sulphur oxides, particulates, carbon monoxide, and water vapour and their effects on surface climate but there appears to be some degree of consensus on the temperature effect of increased CO₂ in the stratosphere. Whether this will be counter-balanced by other types of pollutants and to what degree is not known with any degree of accuracy. Some changes may involve irreversibilities in the natural environment, although no substantive evidence of this is now available.
- (b) There are extremely large uncertainties in the translation of tropospheric climatic changes into quantitative biological effects.
- (c) There are very high uncertainties as to how social communities and the economic system adjust to large-scale climatic changes or even to long-term but small climatic shifts in the biosphere.
- (d) None of these substantial uncertainties is likely to be reduced to accurate estimates of effects in less than one or two decades.

The essential problem is that the relationship between predicted cause and effect is extremely uncertain at this time, but a process of learning over time can be anticipated. The decision process is sequential: decisions made in the next decade can be continued or revoked in future times, and not all decisions on the utilization of the stratosphere need be made at one point in time. Also, impacts of both biological and social consequences may be observed for one or even many human generations after perturbation of the stratosphere. The monitoring and emissions-control costs range from low-cost current techniques such as fuel desulphurization to potentially very high-cost methods of reducing emissions (e.g., removal of CO₂) and of detecting subtle man-induced climatic changes.

These various facets of both extreme uncertainty on climatic effects and relative indecision on actual climatic changes induced by man should lead to, in my opinion, rather simple conclusions on global public policy:

- (a) No large-scale controls affecting human society should be considered for at least 10 years. There just is not enough evidence yet. Possible scenarios of future impacts should be delineated by the academic communities of nations, however.
- (b) Extensive, multilateral co-ordinated studies of both natural climatic variations and man's impact on climate should proceed immediately, with emphasis on the current and potential future effects of industrial activity. A reasonable historical examination should also be made as to how man has been constrained by and has adapted to relatively severe long-term climatic changes, and how he might adapt in the future.

- (c) Each culture or nation must be able to understand how it can or cannot adapt to rather substantial changes in climate and what economic and social safeguards are necessary both within itself and globally to protect its economic viability and to limit potential social and economic stresses due to undesirable climatic effects.
- (d) A research-oriented global policy unit needs to be established within the United Nations to provide leadership among nations in ensuring the long-term welfare of all countries as related to climate change, global effects, and human well-being. This group should have the freedom to identify activities causing waste in developed and developing nations which directly or indirectly influence climatic balance and to suggest changes. It also must provide guidelines to the developed and developing nations in protecting climates.
- (e) Most importantly, nations must realise that there are dependencies beyond international trade, capital transfers and defence. These special dependencies involve the joint utilization of global common resources inclusive of the upper atmosphere. Common utilization suggests a need for cooperative study and regulation.

2. Nature of economic impacts

2.1 Effects of climatic change

Economic adaptation to climatic change is almost unlimited in scope and variety 3. Agricultural crops are planted late or harvested early, and are partially stored for use during exceptionally severe periods of drought or cold. Through genetic selection, hardier or heat-resistant varieties of crops are obtained and applied. Farm operators plant a mixture of crops to protect against climatic extremes and thereby the possible loss of a single weather-sensitive crop. Energy-intensive machinery is utilized to reduce the time for seeding or harvesting. Housing is insulated to reduce heat loss or reduce heat absorption. Industries stockpile raw materials to avoid shortages due to reduced deliveries during inclement weather. Reservoirs are constructed to reduce flooding and provide water during periods of low stream flow or drought. Employers hire additional workers and adjust working hours to reduce production stoppages due to employee illness or inability to travel to work during periods of extreme climate. Special snow removal equipment is purchased and stored in case of severe storms. Individuals purchase medicines, warmer clothes, snow tyres, tyre chains, windshield de-icers, and a multitude of other goods and services in order to adapt to changes in seasonal climate. Thus, a substantial amount of the production of any economy is directly or indirectly used to offset or negate the economic effects of climatic variation. Considering only the purchases by consumers in the northern hemisphere above 40° latitude, the amount spent may be as high as 10 per cent of per capita income 7. In addition, almost all planning of future activities depends to some degree on climatic predictions. The economy's short-term productivity depends on the accuracy of such predictions. Thus, natural climatic variation and inaccuracies in predicting climate are costly to the productive and consumption activities of any economy.

A significant shift in climate over time, either natural or man-made, will induce a different combination of goods and services used to offset the "new" climate. This combination may be less or greater in cost depending on the various elements identifying the climatic change. With higher average temperatures, one might expect that less agricultural machinery investments would be made for reducing seeding and harvesting time intervals. Likewise, there would be a reduction in winter clothing expenditures, snow removal equipment purchases, and other commodities related to cooler temperatures. Alternatively, increased resources may be devoted to cooling systems, refrigeration of foods and perishables, supplemental irrigation applications, and prevention of temperature-sensitive air- and water-borne diseases. The net economic effect on any one nation will clearly depend on how the mix of resources used to adapt to climatic variation will be altered and how the cost of these resources will change in response to a new climate regime. From a regional and national perspective, both the losses and gains may be spread among areas with very different micro-climates and adaptive abilities of local populations in compensating for the climatic change.

These preliminary remarks hopefully provide cautionary qualifications on the global or regional results to be presented in what follows.

2.2 Principles for evaluation of impacts

Economists and other social scientists have long been preoccupied with how human values manifest themselves, and whether these values are measureable among individuals, groups of individuals, or entire societies. One measure of some degree of validity is the concept of gross domestic product (GDP), or the price valuation of all new goods and services produced by an economy in one year. In essence, GDP measures what is produced at current prices, but not what should be produced at socially relevant prices. The GDP, by strict identity, measures costs of producing all market goods and some non-market goods in society. In recent years, the validity of this measure for assessing human values has been severely questioned. There have been recent criticisms of whether all community costs are expressed in the payments-for-resources side of the GDP account, or whether payments (resource costs) accurately reflect either the appropriate combination of resources or socially desirable magnitude of payments among types of resources. Nevertheless, it appears appropriate, as an initial effort, to value gains and losses due to climatic change in terms of the relative values expressed in current market prices. For non-market goods, value imputations of decisions must, because of a lack of a better measuring device, also be based on these current prices. All economic costs and benefits calculated in this paper are based on recent international price levels of goods, inputs, and services in 1974.

In past decades, a large number of alternative measures of costs and benefits have been proposed by economists, including "weighted" costs and benefits depending on social or income class incidence, payment order to compensate the individual so that he is indifferent between the current state and an altered climatic state, and others. Each of these measures attempts to approximate the social loss or gain of a beneficial or adverse event.

There are three basic evaluation principles that have historically evolved in western economics to determine the magnitude of collective and individual gains and losses:

- Alternative cost
- Opportunity cost
- Willingness-to-pay.

Other more advanced valuation principles for evaluating social change have been proposed 3.

The alternative-cost principle basically asks what would be the minimum cost of providing a service or a substitute for a service without consideration of secondary effects, such as substitution possibilities or other indirect adjustment mechanisms. Such substitution possibilities generally include movement or change by the affected party resulting from the use of, say, changes in stratospheric services so that the party does not have to bear the entire cost of this change. As an example of the alternative cost principle, we can look at the problem of changes in precipitation on urban landscapes. One method of evaluating reduced natural precipitation is to measure the cost of providing supplemental irrigation water and other resources to maintain the current urban landscape, given that natural precipitation is reduced. This measure indicates the cost of returning the landscape to its original state following a climatic impact. If the cheapest way of returning a landscape to its original state is by providing supplemental irrigation water, then this is a measure of the alternative cost of the climatic change. If there are no possible ways of providing a natural landscape in an urban setting other than by irrigation water, and there are no substitutes of resources that could compensate urban dwellers for a change in landscape, then the alternative cost measure is a reasonable approximation of cost.

A second important set of measures can be derived from the so-called opportunity-cost principle. This involves an application of the alternative-cost principle. In addition, however, it attempts not only to assess the gross loss to society in terms of alternative provisions of services, but also to consider substitution possibilities, so that a net loss in terms of either income or some other reasonable measure is obtained. For example, a different type of vegetation could be created to compensate for reduced precipitation. The critical measure here is to assess the incremental cost to society of providing completely substitutable vegetation (or other resources) at least cost. Another way of expressing opportunity cost is to derive the minimum amount individuals would accept to be subjected to a given climatic change. Both the alternative cost and opportunity cost measured depend upon existing valuation in markets for various resources.

The willingness-to-pay principle involves the determination of what individuals, collective groups, or both would pay not to be subjected to the climatic change. This principle not only involves the current cost of resources, but also intrinsic preferences or preferences not currently expressed in markets by individuals.

It is difficult to assess the relative magnitude of these various measurements of costs. It is generally true (but not always) that opportunity cost estimate will exceed the willingness-to-pay cost estimate for adverse effects. But

it cannot be asserted the alternative-cost principle will yield an estimate larger or smaller than opportunity-cost criterion. For example, we could assert that in certain instances income compensation for changes in skin cancer incidence rate due to the depletion of the ozone column might be relatively small when we compare this with the alternative cost of maintaining current incidence rate. These principles do offer at least a first approximation of a reasonable market oriented mechanism for the value or loss of climatic perturbation. Other measures of changes in social cost are available in addition to the three listed. However, almost all other measures depend directly or indirectly on specifying gains and losses among groups within and between nations. The specification between group gains, losses, and social welfare involves extremely arbitrary decisions on weights. Consequently, it was thought better at this time to attempt to apply more traditional measures of gains and losses, which are directly related to international prices as an indicator of value or loss. In the tentative empirical estimates that follow, these valuation principles were utilized where they seemed to describe best what might be the actual cost for the sector identified. No attempt is made to defend these principles as applicable to the diversity of value systems internationally. What they do allow is a direct assessment of the magnitude of costs which are comparable with costs reflected in prices of competitive and mixed economies trading in international markets.

The measures of losses and benefits resulting from climatic change cannot be summed over the various impacts to obtain a global loss or benefit measure. Utilizing different valuation methodologies was necessitated by the inadequacy of data in some cases and also that a good measure of loss for one type of impact (residential fuel) appeared to be a poor measure for some other type of impact (rice production). The second qualification is that while the types of impacts reported in this paper span most categories of anticipated effects, the listing is far from comprehensive in any one category, i.e., most agricultural crops are not examined. Thus, not only are there substantial qualifications in utilizing the measures employed to infer changes in global resource use and efficiency, but there are uncertainties as to what the complete impact might be if all affected categories were measured and included.

2.3 An example of climatic impact assessment

The following estimates of economic costs associated with prescribed climatic changes were developed under the auspices of the Climatic Impact Assessment Program, U.S. Department of Transportation. They are highly preliminary and subject to substantive qualification. However, they do provide a rather rough approximation of the sensitivity of various sectors of the global, regional and U.S. economy to particular climatic changes. For illustrative purposes, changes in mean global temperature of -1 deg C and $+0.5$ deg C were examined along with plus or minus 12.5 (or 6.25) per cent change in global mean annual precipitation. Costs or benefits are presented in terms of "present values". In simple terms, "present value" is the amount that would have to be deposited in a bank (in the present) to pay for all future costs of a long-term adverse shift in climate. Alternatively, the present value of benefits reflects what could be taken out of a bank today as a loan and be fully repaid through time from a hypothetical "beneficial" climatic change.

Finally, hypothetical climatic change was presumed to occur over a thirty-year interval, 1990 through the year 2019. This is obviously a highly tenuous assumption, since for some pollutants such as stratospheric aircraft emissions the change may be much faster, whereas for CO₂ and fluorocarbon emissions, the change could be more gradual.

Recorded in Table 1 are a set of preliminary estimates of the effect of a 1 deg C reduction and .5 deg C increase in mean global temperature with precipitation and other climatic variables held constant. These studies for the most part were completed by independent researchers under a grant from the U.S. Department of Transportation. It should be noted that coverage is not worldwide for most of the natural resources, and human and urban impact estimates were derived only for the United States. The magnitude of costs is estimated for a perceived slight reduction in global temperature over a thirty-year time period. For example, 13 marine species of fisheries are estimated to undergo an economic loss associated with catch of more than \$ 28 billion (thousand million) in present value terms, although this entire loss would not occur at any one time. Losses in rice production are estimated to be in excess of \$ 19 billion, which would certainly have a definable impact on many developing nations. The major estimated losses to the United States would be for increases in health, housing and clothing expenditures, and reduced forest yields.

The first study reported in Table 1 was conducted by Drs. Shaul Ben-David and William Schulze, who developed quantitative economic models embodying agricultural production functions relating yield as a function of climate and various climatic variables and agricultural technology. The model also embodies a set of demand functions in which the quantity demanded depended upon price, income, and other factors. Utilizing this model for various regions of the world, Ben-David and Schulze were able to calculate, given a -1 deg C or +.5 deg C change in mean annual temperature, the effects on yield. These changes were then translated into changes in market price and quantity demanded. Given these changes, an estimate of economic loss or benefit is directly obtainable. In some regions, yield decreased while in others it increased. Thus, the estimate of present value cost recorded in Table 1 reflects a net impact on various economic sectors of the world. This net impact does not adequately reflect the regional disparities in impact and changes in yield. Ben-David and Schulze also developed a similar model for world cotton production, and again the net economic effect is relatively small, as was observed with corn. However, this net input does not allow consideration of regional shifts in yields. Their study also does not embody in an explicit way the possibilities of substitution between corn and other staple crops or other types of cloth for cotton. The estimates of economic loss are therefore likely to be biased upwards if there are substitutes for corn and cotton that are non-climatically impacted. The study on wheat production was conducted by Messrs. Mayo and McMillan under my direction and involved estimating wheat production functions as related to climate variables for various major wheat producing nations. They examine several models which indicate that spring wheat (and to some extent, winter wheat) yields are slightly increased in the U.S.S.R. when temperature declines. Offsetting this increase in potential yield resulting from reduced evapotranspiration is a shorter growing season. Whether a reduced growing season or a reduction in potential evapotranspiration requirement will dominate and thereby a mean annual temperature decrease will reduce or increase world wheat production is not now predictable. This will be discussed in more

detail in a later segment of the paper. Dr. Frank Bowman used essentially the alternative cost principle to measure the cost of climatic change in rice production. A substantial amount of world rice production does not enter formal market channels. It is therefore difficult if not impossible at this time to develop region-by-region demand equations. It also appears defensible to say that rice, unlike corn and cotton, is one of the major sources of caloric energy in the world and thereby will not be reduced in production with adverse climatic changes, but in fact will be produced on available land now considered sub-marginal for rice. If this conjecture is defensible, then the application of the alternative cost principle for assessing economic losses due to changes in rice production would be close to being the appropriate measure of society's loss from the perspective of the international community. That is, current world rice production would not be reduced but more inputs to production would occur to maintain it.

The next major sector examined was forest production by Professor G. Schreuder on the effect of a temperature change on forest yields in the United States. Two kinds of impacts were identified in this study:

- (a) a change in the growth rate of trees by region; and
- (b) a change in the area of growth of various species of trees.

The estimates reported in Table 1 for Canada and the U.S.S.R. are extrapolations of yield relations established for the United States. Thus, the estimates of present value cost for these two countries should be viewed with extreme caution and only be considered suggestive of possible magnitudes. Mr. Schmidt, under my direction, conducted a study of Douglas fir production for the U.S. Pacific Northwest. The Schmidt study differed from Schreuder's in that Schmidt estimated economic loss on the basis of the willingness-to-pay principle as opposed to the opportunity-cost principle. The magnitude of the estimates in Table 1 for forests indicates that even over a long period of growth and time interval for the climatic impact to occur (30 years) substantial present value economic losses may still occur. Thus, as might be anticipated, commercial forest productivity is found to be highly sensitive to long-term climatic shifts.

The effect of climatic change on world marine resources (13 major marine species) was examined in depth by Dr. Frederick Bell. Bell includes both commercial and sports fishing losses in computing the estimated economic impact. Bell's estimates for computing loss utilizes the willingness-to-pay principle which may, in fact, substantially underestimate actual global losses, since any large scale adverse impact on fisheries could substantially reduce a major source of human protein. The final economic sector reported in Table 1 was for the impact of temperature change on water resources basins in the United States. The two basins studied were the California and Missouri water resource regions. The effect of temperature change and changes in precipitation on flooding, hydroelectric power generation and availability of irrigation water were examined. An estimate of economic loss based on the alternative cost principle was undertaken. While the findings on water resources appear to be appropriate for highly developed water resource basins in the United States, there is a question whether these results can be generalized for certain less developed water regions in the United States or basins in other parts of the world. The estimates do indicate the magnitude of losses or gains, mostly due to flooding, associated with two highly developed water resources basins.

Table 1

Estimates of Economic Costs of Climatic Change
-1 deg C and +.5 deg C Change in Mean and Temperature

Sector Studied	Investigator(s)	Coverage	Present Value Cost in Millions of 1974 U.S. Dollars*	
			-1 deg C	+ .5 deg C
<u>Natural Resources</u>				
corn production	Schulze, Ben-David	60% of the world	-420	280
cotton production	Schulze, Ben-David	65% of the world	220	-60
wheat production	Mayo, McMillan	55% of the world	1 840	?
rice production	Bollman	85% of the world	19 120	?
forest production	Schrueder	United States	13 220	?
		Canada	5 360	-3 620
		USSR (softwood only)	27 660	-12 660
Douglas fir production	Schmidt	U.S. Pacific Northwest	9 500	?
marine resources	Bell	World	28 620	-12 260
water resources	Bollman	2 U.S. River Basins	-40	100
<u>Urban Resources</u>				
health impacts (excluding skin cancer)	Anderson, Lave, Pauly	U.S. only	47 720	?
wages	Hoch	U.S. only	73 340	-31 020
residential, commercial and industrial fossil fuel demand	Nelson	U.S. only	3 520	-1 760
residential and commercial electricity demand	Crocker, <u>et. al.</u>	U.S. only	-14 960	7 100
housing, clothing expenditures	Crocker, <u>et. al.</u>	U.S. only	10 140	-5 060
public expenditures	Sassone	U.S. only	480	-220

-662-

* Negative sign denotes benefit. "Best estimates" are provided; numbers are reported to within tens of millions of dollars even though they are much less precise than this. Source: 5.

In Table 1 are recorded a selected set of estimates of impacts associated with urban resources. The first study was conducted on the health impacts of a change in climate by Drs. Anderson, Lave and Pauly who examined the covariation between various climatic variables and expenditures for physicians' services posing the hypothetical question that climate is one factor among many that increase the demand for medical care. They also related crude mortality rates to various measures of climate. While this kind of analysis is only approximative, it may at least suggest the extent of changes in health care expenditures associated with climate and how these expenditures vary across different climates within the United States. The second study by Dr. Irving Hoch relates wages to various climatic factors. The central hypothesis is that if the cost of living rises as one moves to different climatic regimes, then wage earners will have to be paid a differential to compensate for this climatic difference. (See also a later study by Hoch 77).

The next urban resource study reported in Table 1 was conducted by Dr. Jon Nelson on how residential, commercial and industrial fossil fuel demands would change in response to a change in temperature. The central proposition is that with cooler temperatures, space heating requirements will increase and thereby induce a loss to the economy. Nelson found a significant covariation between various measures of climatic differences among states in the U.S. and the residential and commercial demand for fuels. In the next study, Dr. Crocker and others have estimated how residential and commercial demand for electricity varies among locations with different climates. Much of the demand for residential electricity is dependent upon air conditioning systems. Thus, while Crocker's results may be appropriate for the United States, they are unlikely to be highly accurate if applied to other climatic zones of the world. Another study by Crocker and his colleagues reported on in Table 1 examines how housing and clothing expense changes with temperature. They found that, on the average, in colder climates consumers spend more for housing (as reflected in greater insulation needs) and clothing. The final study reported in Table 1 was conducted by Dr. Peter Sassone who examined the relationship in the United States between temperature and other climatic variables and expenditures by public agencies. He found there were substantial increases in costs associated with snow removal, road salt and other local expenditures in response to lower temperatures.

The estimates reported in Table 1 are highly speculative and depend on a large number of assumptions regarding the economic sectors studied. They do indicate roughly direct economic costs or benefits of a change in climate as represented by a long-term shift in mean annual temperature. These estimates also indicate that most developed economies are temperature dependent in terms of costs to the economy of offsetting climatic variations. The magnitudes of these economic costs are sizeable but do not constitute a very significant component of either world or U.S. gross product. In addition, these estimates do not represent the very likely large scale differences in effects among nations because of climatic change. For example, a large negative change in mean global temperature would probably have a much greater adverse effect on Soviet wheat than on the U.S. wheat crop. Yet this diversity of impact is not reflected in the estimates provided in Table 1. It is in effect "netted out", as are regional disparities in impacts between the northern latitudes of Canada, Soviet Union and southern latitudes.

In Table 2 estimates of the change in present value costs resulting from a mean annual temperature change and also a positive or negative change in precipitation are presented. The 12.5 per cent (6.25 per cent) increase or decrease in precipitation examined in Table 2 is entirely arbitrary but is applied to indicate the degree of sensitivity of a combined effect of temperature and precipitation change. For corn and cotton production, employing the models of agriculture production functions, shifts are all quite small; that is, a positive or negative change in precipitation has little net effect on economic loss across various regions of the world. However, for particular regions this impact is likely to be large. For marine resources, the estimates indicate that temperature changes coupled with precipitation changes are likely to amplify the economic loss substantially for negative changes in temperatures and be somewhat offsetting for positive changes in temperature. While fossil fuel demands do not seem to be sensitive to combined temperature and precipitation changes, public expenditures do; that is, a negative change in temperature accompanied by an increase in precipitation is more costly than a negative change in temperature coupled with an offsetting decrease in precipitation. In Table 2, there are many question marks on estimates of the present value cost of various combinations of temperature and precipitation changes. Unfortunately, there appear to be no existing studies that allow quantitative estimates to be made at this time.

If wages, at least in part, reflect cost of living differentials between various climatic regions of a nation, then it should be anticipated that additional direct costs to the consumer should approximately be equal to wage differences observed among different climate regimes. In Table 3 is a comparison for the United States of wage differences between different climatic zones when other factors affecting wages are netted out. In addition, some of the differences in additional direct costs to consumers are listed. Of course, some types of indirect costs to consumers including preferences for good weather, types of recreation activity, etc., are not included. It is striking in terms of results presented in Table 3 that the magnitude of costs associated with climate expressed by wage differences in the United States and cost of living differences as represented by some categories of direct costs are so close. This provides some degree of verification of at least the order of magnitude of costs of living differences associated with changes in climates. The estimates in Table 3 can be interpreted as indicating the approximate additional cost to consumers of living in a climate which is 1 deg C colder. In the next section of this paper, a more detailed discussion of changes in expenditures of consumers for heating and air conditioning will be undertaken based on recent results.

In summary, there is substantive evidence of direct economic linkages between economic costs and different climates as represented by differences in mean annual temperature. In particular, colder climates will be more costly for agricultural production, forest production, and marine resources. Colder climates will also require more urban resources for sustenance, although there may be offsetting factors between heating and cooling requirements. Second, while some very crude quantitative estimates of economic costs have been presented, they are far from being definitive or complete for policy-making purposes. Most of the estimates were presented for a single country with distinct climatic attributes. Thus, these estimates must only be viewed as suggestive of how sensitive various nations other than the United States might be to long-term climatic changes.

Table 2

Sensitivity of Economic Costs to Precipitation Change
Selected Economic Sectors

Sector Studied*	Present Value Cost in Millions of 1974 U.S. Dollars**					
	-1 deg C Mean Annual Temperature			+ .5 deg C Mean Annual Temperature		
	No Change in Precipitation	12.5% Increase in Precipitation	12.5% Decrease in Precipitation	No Change in Precipitation	6.25% Increase in Precipitation	6.25% Decrease in Precipitation
<u>Natural Resources</u>						
corn production	-420	-400	-420	280	280	300
cotton production	220	200	180	-60	-80	-60
wheat production	1 840	?	?	?	?	?
rice production	19 120	21 660	18 360	?	?	?
forest production (U.S. only)	13 220	?	?	?	?	?
Douglas fir production	9 500	7 300	11 660	?	?	?
marine resources	28 620	35 720	48 680	-12 260	-14 100	-1 176
water resources	-40	200	2 100	100	1 080	120
<u>Urban Resources (U.S. only)</u>						
health impacts (excluding skin cancer, U.S. only)	47 720	129 700	37 920	?	?	?
wages	73 340	37 220	108 900	-31 020	-31 000	-31 040
residential, commercial and industrial fossil fuel demand	3 520	3 520	3 520	-1 760	-1 760	-1 760
residential electricity demand	-14 960	?	?	7 100	?	?
commercial electricity demand						
housing, clothing expenditures	10 140	?	?	-5 060	?	?
public expenditures	480	720	300	-220	-340	-120

* Sectors correspond with those identified in Table 1.

** Negative sign denotes benefit.

Table 3

Comparison between wage differentials and estimated direct additional costs, United States only (-1°C. Change in mean annual temperature, no change in precipitation, 5 per cent interest rate assumed)

Potential Impact	Method of Measurement	Present Value Cost in 1974 (millions of U.S. Dollars)***
Wage differences	Cross section (by state) multiple regression analysis by skill category	73 340
.....		
Additional Direct Costs		
1. residential, commercial, industrial fossil fuel demand	Cross section (by state) multiple regression analysis for each use, differences in expenditure	7 740
2. electricity used in commercial buildings	Regression analysis of data on individual commercial buildings	10 947*
3. electricity used in residential buildings	Derived from commercial electricity demand regressions	-820
4. personal budget costs (clothing, housing, miscellaneous)	Cross section regression analysis by state	10 140
5. public costs on roads, snow removal, etc.	Cross section regression analysis by state	480
6. materials weathering	Not measured	
7. health costs**	Cross section regression analysis of health expenditure and crude mortality rates	47 720
Sum of additional estimated direct costs, noting that potentially important cost and benefit estimates are omitted		76 207

* Estimate is probably too high since no adjustment is made for substitution of future buildings toward less costly energy sources.

** Health costs include an adjustment for a 2.5% reduction in wind speed. If the wage differential were adjusted for this, it would mean an approximate 4-8% reduction in loss as measured by wages.

*** See footnote in Table 1 for qualifications on the precision of estimates.

3. Benefit-cost analyses

In this section, several crude benefit-cost analyses are conducted for assessing whether controls on emissions are currently justified. The estimates contained herein are highly tentative and should be viewed as illustrative of possible ranges of economic costs and benefits.

3.1 Stratospheric aircraft

Table 4 is a preliminary benefit-cost analysis based on the measured environmental damages reported in Section 2 of this paper and control costs are given. Table 4 contains estimates of the damages avoided by desulphurization of jet fuel used in supersonic aircraft (from climatic change induced by aerosols) along with costs associated with sulphur removal. It is seen that for various fleet sizes of supersonic aircraft flying in the year 2000, the benefit-cost ratio for desulphurization exceeds 2.5. However, it is to be noted that damages avoided are computed on the basis of assuming proportionality over the range 0 to -1°C and examining the narrow range of 0 to $-.007^{\circ}\text{C}$. The mean temperature change resulting from various possible fleets is now very uncertain. Some scientists have indicated the most likely change is negative but very slight, between $7/1\ 000$ and $14/1\ 000$ deg C. It is conceivable but not probable that the negative change could be as high as 0.5 deg C. There is an additional problem in that fuel desulphurization takes account of aerosol impact on climatic change; but there is a countervailing impact from injection of water vapour, which on balance is predicted to raise surface temperature via the greenhouse effect. Desulphurization alone could conceivably induce an even greater warming effect from water vapour injections. Until more precise meteorological models can be constructed on a global basis so that the joint effect of water vapour and aerosols can be more accurately predicted, the benefit-cost ratio calculated here for sulphur removal must be viewed with extreme qualification.

Table 4

Climate change - Preliminary estimates of costs and benefits
for fuel desulphurization

Number of Planes*	Present value cost 1974 5% rate of interest (millions of U.S. dollars)	
	<u>Damages avoided</u>	<u>Desulphurization</u>
200	240	92
400	480	186
600	720	278
1 000	1 200	464
	($-.007^{\circ}\text{C}$ Probable Change)	

* Second generation supersonic aircraft flying in the year 2000.

Economic costs induced by alteration in the amount of ultra-violet (UV) radiation contacting the Earth were estimated for skin cancer (non-melanoma) and materials. Materials weathering costs associated with increased UV radiation were estimated for plastics, textiles, paints, and other surface finishes. Many other potential impacts including increased skin aging, sunburn, and biological processes dependent on the UV spectrum were not measured. In Table 5 are listed measured damages avoided and estimated costs associated with redesigning jet engine combustion to reduce NO_x emissions by a factor of six.

Table 5

Ozone depletion - Preliminary estimates of costs and benefits
for engine redesign

Number of Planes*	Present value cost 1974 5% rate of interest (millions of U.S. dollars)	
	<u>Damages avoided</u>	<u>Redesign costs</u>
200	560	110
400	1 040	150
600	1 600	190
1 000	2 760	270

* Second generation supersonic aircraft flying in the year 2000.

For fleet sizes from 200 to 1 000 airplanes, all computed benefit-cost ratios exceed four. Among countries, ozone depletion effects are highly diverse since incidence rates for skin cancer are much greater for light skinned Caucasians and for individuals who spend large amounts of time in the sun. For countries where there is relatively little activity out of doors, changed UV radiation should have only minor effects on skin cancer incidence rates. Alternatively, for nations with very substantial levels of outdoor recreation activity, skin cancer incidence rates are likely to increase. Because of the negative impacts of ozone depletion for areas that were not included and the method of estimating damages, a greater degree of confidence might be placed in the estimated benefit-cost ratios for UV related effects compared with those for temperature change. In the benefit-cost estimates presented for ozone depletion and for climatic change, there is a substantial difference in the sheer magnitude of damages that may occur; but it appears that the climatic estimates are subject to a much greater degree of uncertainty.

It seems clear from these preliminary benefit-cost analyses on aircraft that (1) the stratosphere is a potentially sensitive resource to man's activities and not enough is known about it currently to predict consequences accurately either in an efficiency or distributional sense; and (2) suspected impacts tend to be negative and of a long-term character. Increased exposure to UV radiation today

means an increased probability of contracting skin cancer in 30 years, and a gradual build-up of aerosols in the atmosphere may require 60 years to be noticeably reflected in long-term trends of surface temperature.

3.2 Analysis of fluorocarbons

Recently concern has been expressed as to the impact of fluorocarbons on the ozone concentration in the stratosphere and on the impact of these same compounds on world climate. According to the IMOS report [8]:

"Although the theory of possible ozone reduction (in the stratosphere) by fluorocarbons 11 and 12 (F-11 and F-12) cannot be presently supported by direct atmospheric measurements, the matter has been carefully studied independently by many scientists. Thus far, the validity of the theory and the predicted amounts of ozone reduction have not been seriously challenged. More research is required and will be undertaken, but there seems to be legitimate cause for serious concern."

A simplified sketch of this concern might be as follows. Fluorocarbons after or during economic use escape and ultimately collect in the stratosphere. In the stratosphere, these chemicals interact with ozone and other chemical constituents, initiating a reduction in ozone and perhaps a change to plants and animals, including humans. The climatic changes are presumed to induce another set of adjustments to organic life. The major question is whether, on balance, these changes are beneficial or adverse to humans.

Fluorocarbons, for the most part, are not purchased directly by households but are utilized as inputs to produce consumer products or services. In consequence, the observed demand relationships for fluorocarbons do not directly relate to consumer valuation but rather indirectly through demand for products utilizing fluorocarbons. Under some specialized circumstances, final product demand and consumer surplus will be exactly representable by the derived demand and surplus for fluorocarbons such that observed losses in "derived" surplus would be equivalent to loss in consumer surplus in final goods markets. Unfortunately, observed data on prices and quantities sold historically may not adequately reflect actual dependencies between final product demand and surplus and derived demand and surplus. In order to obtain reasonable, valid bounds on "consumer surplus", both derived surplus and consumer surplus losses had to be estimated.

Measures of "derived surplus" loss for restrictions in fluorocarbon production were developed for F-11 and F-12 along with measures of consumer surplus loss for the major final products using these fluorocarbons in their production. Other fluorocarbons were not examined. Included in the list of final products were refrigerators, aerosol deodorants, auto air conditioners, polyurethane foam mattresses, and mobile vehicle refrigeration systems. According to the IMOS report, these products accounted for about 90 per cent of U.S. utilization of major fluorocarbons and more than 98 per cent of F-11 and F-12 use in 1972 [8].

In Table 6 are recorded estimates of the present value of derived surplus for F-11 and F-12 and consumer surplus for major consumer products using F-11 and/or F-12 in their production. As is readily apparent from the estimates, "derived surplus" estimates amount to about \$3 billion, while consumer surplus for the major products using them amount to more than \$84 billion. Of course, these estimates would tend to bound the actual value of consumer surplus. On one extreme, if no substitutes existed for producing the final product, the appropriate measure of economic loss would be the sum of consumer surplus losses in the final markets impacted whereas, if there were such substitution possibilities, it would appear appropriate to utilize the "derived surplus" estimates.

It has been hypothesized that F-11 and F-12 emissions will induce two global effects:

- (a) reduction in stratospheric ozone and increase in biologically active UV radiation at the Earth's surface; and
- (b) a slight rise in surface temperature due to an increased transparency of the stratosphere resulting from ozone depletion.

Both of these global effects, if they occurred at a significant level, would have large scale ramifications on biological life and thereby on the U.S. and other nations' economies. It would seem to be impossible empirically to estimate the thousands of interrelated impacts of changes in surface micro-climates. In the partial analysis which was undertaken, costs and benefits were estimated for some major sectors of the U.S. economy from ozone depletion or enhancement and for slight long-term increases in surface temperature. The U.S. sectors and/or components of them included are:

- (a) Ozone depletion
 - (i) Non-melanoma skin cancer
 - (ii) Materials weathering (polymeric materials)
- (b) Temperature change (induced by ozone depletion)
 - (i) Marine resources
 - (ii) Forest products
 - (iii) Agricultural crops
 - (iv) Urban resources (fossil fuel, electricity, housing, clothing and government expenditures).

The major question is whether, given the evidence, F-11 and F-12 should be regulated as to production and/or emissions and to what degree. It is clear from a simple comparison of Tables 6 and 7 that the present value of net benefits of a complete ban of fluorocarbons production is positive if "derived surplus" is used as a measure of social cost and negative if the sum of "consumer surpluses" is used as the relevant measure.

Table 6

Estimates of consumer surplus and derived surplus* for selected products, United States, 1971 Dollars
(Present value 1974, 5 per cent discount rate in millions of dollars)

Commodity	Estimated 1973 Expenditures by Commodity**	Consumer Surplus or Derived Surplus (Present Value)***
1. F-11	40	2 201
2. F-12	96	740
3. Refrigerators	1 386	39 727
4. Mobile vehicle refrigerator systems	97	3 349
5. Auto air conditioners	489	36 473
6. Polyurethane foam mattresses	39	1 007
7. Aerosol hair care products	134	2 679
8. Aerosol deodorants and antiperspirants	458	9 165
9. Aerosol perfumes, cosmetics and toiletries	346	6 919
10. Aerosol room deodorizers	60	1 200
11. Aerosol pharmaceuticals	38	752
12. Aerosol shaving products	40	795
13. Aerosol insecticides	258	5 168
Total minus F-11 and F-12	3 345	107 234
Total for aerosol products	1 334	26 678
Total for non-aerosol products	2 011	80 556

* Area under the derived demand curve less equilibrium purchases in 1973.

** Expenditures are estimated from the estimated demand relationships rather than actual data since actual price may deviate from predicted prices as given by the estimated demand relationship.

*** See footnote in Table 1 for qualification on precision of estimates

Table 7

Estimates of Environmental Costs by Category Due to Current Levels of F-11 and F-12 Emissions, United States, 1974 into Perpetuity.
(millions of 1971 dollars)

Category of Impact	Cost or Benefit*
1. Ozone Depletion	
1.1 Non-melanoma skin cancer**	52-206
1.2 Materials weathering	569
1.3 Biomass productivity	(not estimated)
2. Temperature Change (ozone induced)	
2.1 Marine resources	-661***
2.2 Forest products	-11 060
2.3 Agricultural crops	
2.3.1 Corn	269
2.3.2 Cotton	-16
2.4 Urban resources	
2.4.1 Fossil fuel use	-5 719
2.4.2 Electricity use	45 617
2.4.3 Housing and clothing expenditures	-11 377
2.4.4 Public expenditures	-696
	16 357
Total	16 357

* Costs are expressed as present value of all future costs and benefits resulting from the emission of F-11 and F-12 produced in the year 1973 and maintained at that level into perpetuity. A 5 per cent rate of discount was utilized to convert to present values.

** Non-melanoma skin cancer costs are estimated at \$325/case and \$1 292/case 5.

*** Negative sign denotes benefit. Recent results by Ivar Strand at the University of Maryland indicate that the benefits may in fact be costs. Strand estimates that the costs for U.S. marine resources of uncontrolled emissions may be as high as \$300 million. See Ivar Strand, "Impacts of Ozone Depletion on National and International Fisheries", University of Maryland, (July, 1978).

From Table 8 several general conclusions can be inferred. These are:

- (a) A complete ban on F-11 and F-12 may or may not be economically feasible depending on the availability of substitutes. The benefit-cost ratio for a complete ban may range from 0.2 to more than 2.0.
- (b) A partial ban on F-11 and F-12 use in products other than as a refrigerant appears to be economically feasible, although a major end use, hair sprays, has not been included in the benefit-cost comparisons.
- (c) If the hypothesis that fluorocarbon emissions affect temperature through altering the amount of ozone and thereby light reduction is not true, then the economic feasibility of a total ban is questionable.

In Figure 2, the total derived surpluses are contrasted with total environmental costs over various discount rates. While total environmental costs undiscounted are highly non-linear, the discounting process made them "flatten" out when computed on an annual basis. The important finding, however, is that the degree of "optimal" regulation is highly sensitive to both the discount rate selected (none at 8 per cent) or (75-100 per cent at 3 per cent), and whether fluorocarbons induce a positive temperature change.

For comparative purposes, a set of alternative strategies for U.S. action was developed. The alternative strategies examined reductions in U.S. production of F-11 and F-12 commencing in either 1978 or 1979 along with various actions by the OECD and other nations. These strategies were examined in order to provide insight into whether U.S. benefits and costs for reducing fluorocarbon emissions might be altered substantially by other nations' decisions on regulation. This might occur because environmental costs to the U.S. are directly related to global emissions (and thereby only partially to U.S. emissions). The seven strategies examined are:

- (A) U.S. takes unilateral action. No other nations take action to reduce F-11 and F-12 production. Production levels in the U.S. are reduced to 50 per cent in 1978, 30 per cent in 1980, and 10 per cent in 1982. A steady state of 10 per cent is presumed thereafter.
- (B) Strategy (B) is the same as strategy (A) except for a one-year delay in reductions in production levels such that U.S. production is reduced to 50 per cent in 1979, 30 per cent in 1981, and 10 per cent in 1983.
- (C) U.S. and other OECD nations take identical actions commencing in 1977. World production levels then are reduced to 75 per cent in 1978, 62.5 per cent in 1980, 57.5 per cent in 1981, 55 per cent in 1982, and 40 per cent in 1983.
- (D) Same as strategy (C) except a one-year delay is introduced into implementation of regulations. Thus, the long-term reduction in world production to 40 per cent is reached in 1983 rather than in 1982.

- (E) All countries in the world act similarly. World production drops to 75 per cent in 1978, 50 per cent in 1979, 45 per cent in 1980, 35 per cent in 1981, and reaches a long-term level of 20 per cent in 1982.
- (F) Same as strategy (E) except implementation of regulations is delayed one year such that world production drops to 20 per cent in 1983 rather than in 1982.
- (G) All countries maintain 1973 F-11 and F-12 production into the indefinite future.

Table 8

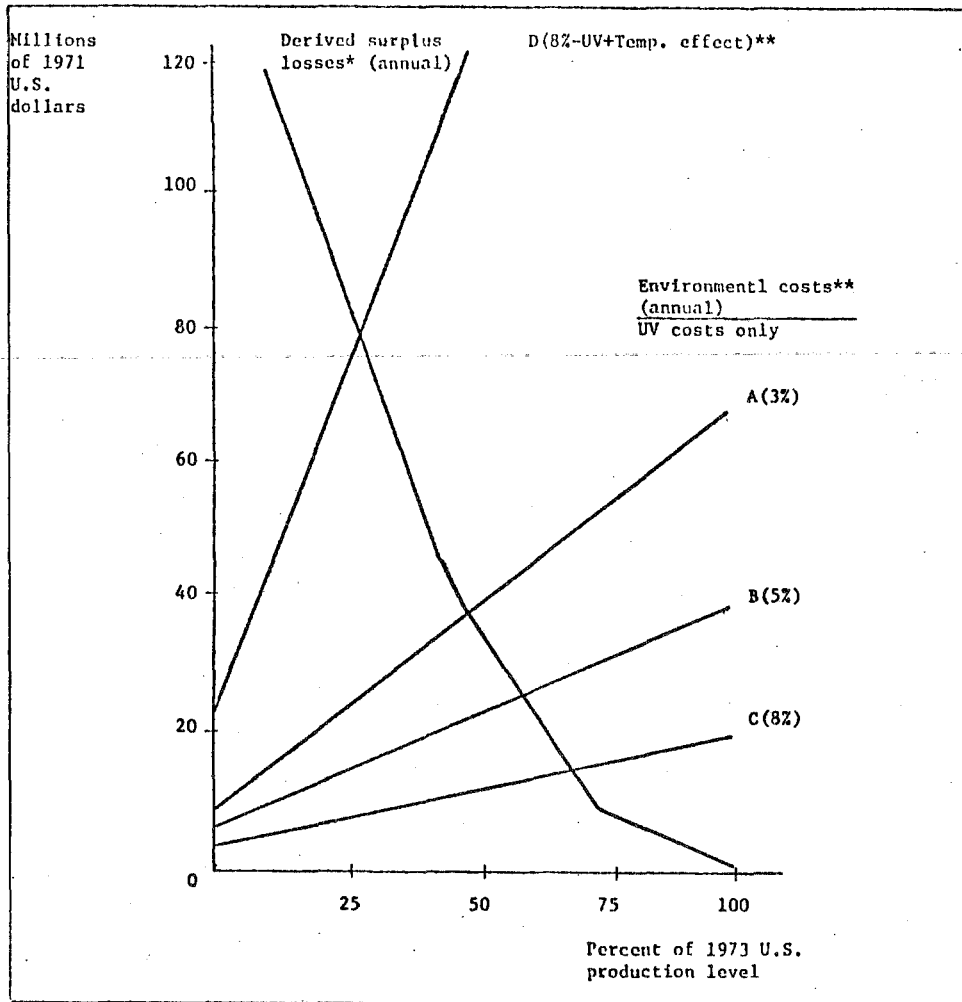
Simple benefit-cost comparisons for a ban on production of fluorocarbons 11 and 12, United States, 5 per cent discount rate, present value 1974.
(millions of U.S. 1971 dollars)

Measure of Costs and Benefits	Benefit* Estimates	Cost** Estimates	Benefit-Cost Ratio
Derived surplus	16 978-17 132	2 942	5.8
Final product consumer surplus***	16 978-17 132	107 234	.16
Derived surplus (plus omission of temperature impacts)	621-775	2 942	.21-.26
Final product consumer surplus (refrigerators, mobile refrigeration systems and automobile air conditioning uses excluded)	9 508-9 594	27 685	.34-.35

* Measured by savings in environmental costs of 1973 level production of F-11 and F-12 in present value terms.

** Loss in consumer or derived surplus at 1973 use rates in present value terms.

*** Includes consumer surplus loss for refrigerators, auto air conditioners, mobile refrigeration systems, polyurethane foam mattresses, aerosol deodorants and antiperspirants, hairsprays and care products, insecticides, pharmaceuticals, cosmetics, perfumes, deodorizers, and shaving products.



* Derived surplus losses as estimated directly from demand curves for F-11 and F-12. Marginal production costs are assumed constant.

** Environmental costs as measured by skin cancer and materials weathering. Cases A, B and C do not contain temperature related costs and coincide with application of 3, 5 and 8 per cent discount rates, respectively. Case D includes estimate of temperature related costs.

Figure 2. Annual derived surplus losses and environmental costs, 1973, U.S.

In Table 9, estimates of U.S. benefits and costs are recorded for these various strategies. The larger the number of countries involved in reducing production of F-11 and F-12 the larger the benefits to the U.S. Second, the feasibility of the alternative strategies depends crucially on the accepted rate of discount and on whether other countries participate in reducing production levels. Third, the feasibility of strategies depends on the method of assessing consumer surplus losses. Utilizing a 3 per cent discount rate, all strategies are economically feasible for the U.S., acting either unilaterally or multilaterally. At 5 per cent, all

strategies would be economically feasible for the U.S. using the derived surplus measure of loss, but only strategies (E) and (F) would be feasible if the consumer surplus measure (with substitution after 10 years for refrigerants) was the correct measure of loss. Fourth, strategy (G) denotes environmental costs to the U.S. when 1973 production levels of F-11 and F-12 continue into the indefinite future. Note that because of the extended time horizon for impacts, the present value using a 3 per cent discount is 25 times higher than that measured at 8 per cent. Thus, it is not surprising that the economic feasibility of strategies depends crucially on the magnitude of the discount rate, i.e., even very substantial future environmental costs have small present values. Fifth, if a relatively low discount rate is given, it will be economically feasible for the U.S. to reduce F-11 and F-12 production even though other countries do not do so. The benefits of unilateral action by the U.S. outweigh the costs.

Table 9

Environmental costs savings less surplus losses, selected strategies for controlling fluorocarbon emissions, United States, present value in 1974.
(millions of 1971 U.S. dollars)

Strategy (See text for description)	Discount Rate (per cent)		
	3	5	8
A	17 201* (7 880)**	3 827 (-4,720)	-589 (-9 876)
B	16 138 (7 487)	3 127 (-3 790)	-590 (-6 772)
C	30 317 (16 823)	7 984 (-5 270)	254 (-11 430)
D	25 915 (15 238)	6 547 (-3 378)	-5*** (-8 795)
E	39 949 (33 025)	11 272 (4 297)	1 112 (-5 252)
F	32 583 (28 317)	9 032 (4 640)	855 (-3 274)
G	57 792	17 133	2 447

* Derived surplus measure of loss is applied here.

** Consumer surplus measure of loss with 10-year lag for refrigeration systems is used in estimates within parentheses.

*** Belongs in category where both estimates are negative.

3.3 Stratospheric pollution due to nitrogen fertilizers

Very little empirical evidence has been developed to assess the effect of nitrogen fertilizers on the stratosphere. However, in a recent study [9] using the damage estimates presented earlier for fluorocarbons, a rough assessment was developed for the impact of nitrogen fertilizers. Worldwide use of nitrogen fertilizer is about 30 to 40 million metric tons per year, and such use is critical for providing high yields of most food crops. In consequence, unlike fluorocarbons or aircraft, the potential losses due to restrictions could be enormous both in terms of basic dietary needs and related health effects. The present value of damages per metric ton is \$310.00, where \$287.00 is accounted for by climatic changes and the remainder by direct ultra-violet radiation effects. Thus, on a worldwide basis, damages could be as high as \$11 billion, certainly not an insignificant amount but small in relation to the benefits of nitrogen fertilizers for augmenting food supplies. The benefit per ton may well exceed \$2 500.00 to \$3 000.00 on a present value basis. This very crude assessment is suggestive that it would be productive to examine the possibility of substitutes for nitrogen fertilizer such as improved cultivation or reduced runoff, particularly in the developed nations. It is also suggestive of the very strong need for international regulatory agreement on pollutant loadings to the stratosphere and the very high potential payoff of greater accuracy in predicting the climatic effects of chemicals entering the stratosphere.

3.4 Carbon dioxide

In recent years the scientific community has become concerned with the rise in atmospheric carbon dioxide resulting from the burning of fossil fuels and deforestation. Because of the so-called greenhouse effect this increase in carbon dioxide through time may lead to a gradual warming of the Earth's surface and movement of various climatic zones.

The economic effects of such a gradual warming of the global surface of from 1.5 deg C to 3 deg C in 40 to 80 years is almost impossible to predict. However, it appears that on balance global agricultural productivity would increase but is highly dependent on how patterns of precipitation change as well [10]. But, both positive and negative changes in economic value can occur. For example, the U.S.S.R. may undergo slight reductions in yield for both spring and winter wheat crops given an increase in temperature with no compensating change in precipitation patterns [5].

A general warming will reduce the use of petroleum, electricity and natural gas for space heating equipment and increase the amount of electricity used for space cooling. Table 10 gives estimates for various regions of the United States of changes in residential consumption of energy for various changes in temperature and indicates that on balance a gradual warming will result in a net saving of energy for all regions of the United States. That is, the reduction in energy use from lower space heating requirements would more than offset the increased energy needed for space cooling. However, this current estimate does not consider the likely future expansion in demand for space cooling of population movements toward warmer climates currently taking place in the U.S. Both of these factors may well cause the net energy saving estimate to become a net economic cost in the long term.

Table 10

Predicted changes in residential consumption of energy in million BTU per capita as a function of temperature change, by region and energy source

	Temperature Change				Base Usage (million BTU* per capita)
	-2°C	-1°C	+1°C	+2°C	
<u>Petroleum</u>					
U.S.	2.927	1.413	-1.325	-2.569	19.536
Northeast	5.395	2.615	-2.466	-4.797	39.472
North Central	2.729	1.307	-1.208	-2.331	16.788
South	2.182	1.055	-0.988	-1.913	12.471
West	1.179	-.558	-0.540	-1.058	9.155
<u>Natural Gas</u>					
U.S.	2.401	1.181	-1.141	-2.245	29.179
Northeast	1.870	0.922	-0.895	-1.766	25.840
North Central	2.858	1.413	-1.381	-2.731	41.649
South	2.101	1.024	-0.976	-1.908	17.367
West	2.945	1.445	-1.395	-2.743	35.243
<u>Electricity</u>					
U.S.	-0.391	-0.196	0.196	0.394	8.395
Northeast	-0.229	-0.113	0.115	0.230	6.150
North Central	-0.243	-0.124	0.126	0.252	7.520
South	-0.634	-0.317	0.317	0.635	10.571
West	-0.409	-0.205	0.205	0.410	8.957
<u>Total, Three Sources</u>					
U.S.	4.937	2.398	-2.270	-4.419	57.109
Northeast	7.036	3.424	-3.247	-6.332	71.461
North Central	5.344	2.597	-2.464	-4.808	65.957
South	3.650	1.762	-1.647	-3.184	40.409
West	3.713	1.814	-1.733	-3.389	53.355

* 1 BTU = 1 055.87 J. (Source: [7].)

Table 11

Changes in expenditure for energy, selected U.S. Cities,
for given changes in temperature
(dollars per year)

City	Altitude in feet	Latitude	Longitude	Mean Annual Temperature in 1977 (°C)	Change in spending per customer Given temperature change			
					-2°C	-1°C	+1°C	+2°C
Portland, Maine	40	43°39.2'N	70°15.7'W	6.9°	+13.66	+ 6.19	- 4.93	- 8.59
New York City	30	40°42.5'N	74°00.0'W	11.3°	-12.73	- 7.31	+ 9.18	+20.30
Baltimore, MD	32	39°17.3'N	76°37.0'W	13.5°	- 7.74	- 4.46	+ 5.58	+12.44
Shreveport, LA	204	32°30.5'N	93°45.0'W	18.3°	-23.18	-12.17	+13.34	+27.85
Madison, Wisconsin	863	43°04.2'N	89°23.6'W	7.6°	+ 2.50	+ .79	+ .11	+ 1.12
Tucson, Arizona	2 389	32°13.0'N	110°58.1'W	20.8°	-47.44	-20.70	+22.00	+45.31
Cheyenne, Wyoming	6 098	41°08.3'N	104°48.8'W	7.9°	+ 2.95	+ .90	+ .25	+ 1.64
Bakersfield, CA	406	35°22.5'N	119°01.3'W	19.9°	-27.79	-14.40	+15.43	+31.84
Los Angeles, CA	287	34°03.5'N	118°15.0'W	17.5°	+ 3.69	+ 1.39	+ .45	+ .02
San Francisco, CA	63	37°46.5'N	122°25.0'W	13.7°	+18.00	+ 8.50	- 7.47	-13.93

Source: 7.

Estimates of changes in expenditures for energy used in residential consumption for selected U.S. cities, given a temperature change, are given in Table 11 and range from a reduction in expenditure per year for Portland, Maine residents of about \$8.50 to an increase in expenditures for Tucson, Arizona residents of more than \$45.00. These preliminary computations indicate that even within a single nation, some regions are likely to be made better off and others worse off from a gradual increase in surface temperature.

In an important paper on CO₂ control, Nordhaus has demonstrated the economic cost of switching to non-fossil fuel sources in 40 to 40 years to reduce substantially carbon dioxide emissions is relatively small, less than 1/2 per cent of world gross product [11]. If his estimates are correct, then carbon dioxide can be viewed as a relatively manageable potential pollutant where immediate controls need not be considered. What is missing is an adequate assessment of the economic costs and benefits of a gradual increase in temperature.

Recent discussions among scientists suggest a much greater temperature increase of almost catastrophic proportions (3 to 6 deg C increase in northern latitudes) might be possible [12]. Such changes would so alter the present configuration and intensity of economic activities that predictable quantities or even qualitative changes become impossible to estimate or even foresee.

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CLIMATE AND SOCIETY: LESSONS FROM RECENT EVENTS

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1. Introduction

The last several papers presented at this Conference consider climatic impacts on society by sectors of economic and social activity and also by world regions. This paper views the subject from a different perspective, one that first emphasizes extreme weather events: blizzards, droughts, floods, tropical cyclones, tornadoes and storms. Then it considers the long-term human response to their recurrence. Thus, we do not study them as isolated weather events but as prevailing features of climate.

The research drawn upon has been a collaborative effort of many scientists, particularly from the geographic community. Among those attending this Conference who have participated in this work are Academician I.P. Gerasimov /1/ and Drs. A. Mascarenhas /2/ and G.F. White /3, 4, 5/. Specifically, studies were conducted in some 20 countries and at 40 sites, and more than 5 000 people who lived and worked in areas of recurrent climatic hazard were interviewed /5/. Additional observations have been made since 1972 in Australia, the African Sahel, India, and the western United States /6/. From these studies we have tried to assess the hazardous aspects of extreme natural events, their broad impacts upon society and the ways in which vulnerability can be reduced.

Our studies have been further informed by the efforts of the Scientific Committee on Problems of the Environment (SCOPE), specifically its work on environmental impact assessment /7/ and on risk assessment /8/ and also its report on the Climate/Society Interface /9/.

2. Knowledge of hazard

2.1 Impacts on society

The burden of natural hazard is primarily climatic in origin, and it is increasing. In the advanced industrial countries of the world property damages are on the rise, and great loss of life persists or increases in the developing nations of the world. These trends are expected to continue and perhaps to intensify.

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At least three-quarters of the estimated \$40 billion a year of global natural hazard costs originates from three major kinds of hazards of climatic origin: floods (40 per cent), tropical cyclones (20 per cent), and drought (15 per cent). This estimate includes losses of about \$25 billion, and the remainder comes from costs of prevention and mitigation.

Each year, on the average, natural hazard claims the lives of the equivalent of a small city, some 250 000 people per year, 95 per cent of whom are citizens of poorer nations. This great inequity in distribution of deaths is reversed for property losses, 75 per cent of which occur in wealthy countries. But proportionally the burden is still heaviest in developing countries, as shown in the accompanying table of comparative costs for the three great hazards.

This can be understood by noting that the absolute cost of drought in a wealthy nation such as Australia exceeds that of Tanzania thirty-fold, yet the impact on the national economy in terms of the proportion of GNP is reversed, with annual drought costs in Tanzania equivalent to 1.8 per cent of GNP and 0.10 per cent in Australia. Similar comparisons can be made between the costs of floods in the United States and Sri Lanka, and for tropical cyclones between the United States and Bangladesh. In proportional terms, expressed as a per cent of GNP, climate hazard has impacts on poor countries 20 to 30 times heavier than on rich countries.

The same inequality of suffering persists within countries. Landless labourers, old people, women and children were the major victims of the Bangladesh cyclone of 1970 /5/, debt-ridden farmers in the Nigerian drought of 1972 /10/, marginal people in the Kenya drought of 1970-71 /11/, and American Indians in a flood in the U.S.A. in 1972 /12/.

2.2 Basic processes

We think we understand the basic underlying process by which human society encounters hazard in its search for useful and purposeful utilization of the resources of land and sea. The hazardous events are simply the extremes of the distribution of events that make possible our growing of food. There is only a fine line between the flood that washes a crop away and the rainfall that permits it to grow.

In order to reap the useful we adjust our society and economy to cope with recurrent extreme events by a combination of individual and collective action. When these adjustments are inadequate, or the extremes too great, loss of life and property occurs. In the most extreme cases we have disaster. Thus, the impacts of these natural events are joint outcomes of the state of nature and the nature of society. In this perspective a flood and a drought are relative phenomena.

There is some evidence that the long-term trend is for successful adjustment, that is, a reduction in the damage from recurrent events whose frequency occurs on the average of about a human generation, but at the same time there is an increase in the catastrophic effects of those events of still greater rarity /5/.

Table

Selected estimates of natural hazard losses

Hazard	Country	Total population (millions)	Population at risk (millions)	Annual death rate/million at risk	Losses and costs per capita at risk			Total costs as % of GNP
					Damages losses	Costs of loss reduction	Total costs	
Drought	Tanzania	13	12	40	\$.70	\$.80	\$ 1.50	\$ 1.84
	Australia	13	1	0	24.00	19.00	43.00	0.10
Floods	Sri Lanka	13	3	5	13.40	1.60	15.00	2.13
	United States	207	25	2	40.00	8.00	48.00	0.11
Tropical cyclones	Bangladesh	72	10	3 000	3.00	.40	3.40	0.73
	United States	207	30	2	13.30	1.20	14.50	0.04

Source: 5

2.3 Reduction of vulnerability

We are substantially reducing the toll of climatic hazard. We do know how to make things better, how to reduce unwanted impacts in many kinds of situations. There are three basic strategies open to us: to reduce or prevent the climatic events, to limit the vulnerability, and to prevent or mitigate the impacts. In general the broader the range of measures employed to reduce vulnerability the more effective they are. For example, comprehensive programmes employing a spectrum of adjustments limit the impacts of floods in the United States, water shortage in Israel, and avalanches in Switzerland.

However, "more" is not always "better". There are situations in which a society may actually be better off to suffer a rare or unexpected loss than to divert its scarce and needed resources to prevent such an occurrence. And there are common situations in which attempting to make things better may make things worse in the long run, a classic example being the use of levees for flood control. Such limited flood control frequently encourages an expansion in flood plain occupancy, thereby exposing more people and property to flood in the rare instances when the levee is overtopped. The water then trapped on the wrong side of the levee causes far greater damage than would have been the case in an unprotected flood plain. Such was the case in 40 per cent of the "protected" flood plains inundated in the United States by Hurricane Agnes in 1972.

2.4 Inadequacy of knowledge

As in all scientific study, as these findings and insights accumulated we also began to learn where our knowledge was inadequate. Here are three examples of our ignorance that will surely relate to the entire range of climatic impacts we will study in the future.

2.4.1 Reducing vulnerability in the face of inequality

We do not know how to reduce the harmful impacts of climatic events in the face of great inequality within and between social systems. Consider the conflicting interpretations of what happened during the Sahelian drought of 1968-1972.

According to the first and seemingly dominant view among scholars /13/, the Sahelian drought found the affected population more vulnerable to its impacts than in the past. It has thus been claimed that the Sahelian people are the victims of a colonial and neocolonial international, economic and technical order, one which increases their dependency and reduces their self-sufficiency by decreasing the area devoted to food crops, by draining off the agriculturally important labour supply by migration, by creating technical conditions for a rapid increase in population and livestock numbers, and by adopting policies that favour the small urban élite. Proponents of this position of increasing vulnerability may emphasize one or another element: neocolonialism, population, land-use, technology, etc.

The competing view holds that the recent Sahelian drought with all its attendant difficulties saw a reduced vulnerability to drought than in past periods /14/. This occurred because the Sahelian nations could call upon the conscience of

the world for assistance, upon extended families which were not entirely dependent on vulnerable crops or herds, upon modern medical care which controls the childhood disease epidemics that often accompanied famines in the past, and even upon a rudimentary infrastructure and national organization which were available, together with international aid, to assist great numbers of people. Only where governments failed to act (as in Ethiopia /15/) or in especially remote areas was there great loss of life.

Depending on which view summarizes the actual Sahelian experience, strongly contrasting policy implications follow. The latter view, essentially the "modernization" thesis, appears still to dominate the development policies of the Sahelian countries themselves. Despite some effort to acquire food self-sufficiency much, if not most, of the development effort is oriented towards improving accessibility of rural areas and towards land and water development - at a cost that makes a significant effort in export crops a necessity. At the same time the structural dependency of the nations involved has, if anything, increased over time, and supplemental labour incomes have become increasingly important. However, if the former view, the "underdevelopment" thesis, is correct many of the current and future programmes, well-intended as they may be, will only increase vulnerability to the next climatic fluctuation. Similar contrasting issues can be found elsewhere in Africa and also in Asia and Latin America.

2.4.2 The role of perturbation in complex social systems

We social scientists share with the geophysical scientists ignorance of the effects of perturbations on complex systems - in our case, social systems. Consider an example that contrasts with the Sahelian drought, the severe drought that occurred in California in 1976-1977. This seriously affected both urban and agricultural systems, but there were surprisingly modest overall repercussions. The trend toward self-sufficiency in underground water accelerated, urban areas successfully cut water use by upwards of 50 per cent, and, with some minor exceptions in certain crops and water using activities, a major disaster was averted.

In fact, a review of a series of disaster impact studies reveals that this pattern of successful coping with perturbations is the typical pattern in an industrialized country such as the United States /12, 16/. Nevertheless, in recent years we have had the greatest flood in our history in terms of property loss, and we do not really understand the detailed factors that have separated successful dampening from amplification.

2.4.3 Slow, pervasive, cumulative change

Finally, we do not understand how to deal with slow, pervasive, cumulative change, such as might occur with future climatic change and currently does occur with erosion and desertification and persistent downturns in moisture availability. In all of the excellent documentation for the United Nations Conference on Desertification (1977) /6/ we could find only one study in which people subject to desertification were asked to comment on their own perceptions of its cause and manifestation /17/. This contrasts with our good understanding of people's response to more acute extreme events.

3. Lessons to be drawn

There are three central lessons to be drawn from the experience with extreme events and from the discussions at this Conference. The first is the need to act upon what we already know, the second is to recognize fully the challenge of climatic impact analysis, and the third is to understand the basic value judgements involved in responding to climate information under conditions of uncertainty.

3.1 Acting upon what we know

Despite the great scientific uncertainties reflected in this Conference we already know much of value with which to enhance human security and make better use of the climate resource. We do not need to decide on the question of increasing, decreasing, or continuing variability. It is sufficient to note that much, if not most, economic planning in the world has been carried out with the current central tendency (averages or means) of climate together with an assumption of little or no variability. Nor is there need to estimate the probability of a melting of the Antarctic ice sheet and subsequent sea level rise to observe the peril of the continued and rapid growth of settlement along the shore at less than three metres above sea level. In the United States, for example, there is a population the size of Boston occupying the three-metre zone in the stretch of coast between Boston and Washington /18/, and in the Bay of Bengal perhaps 15 per cent of the 90 million people of Bangladesh live in such an area /5/. And we do not need to determine the regional impacts of a hypothesized one-degree change in temperature to observe that in many countries commercial non-food crops often pre-empt the best land and the best climate, relegating critical food production to marginal areas /13/, and that access to technologies such as high-yielding, drought-resistant seed is often limited to the largest and wealthiest farmers /11/.

Thus, a world climate programme needs to include from its earliest inception a major component, namely the distillation and synthesis of what we already know about climatic variability, extreme events, climatic resource areas, and the range of potential human adjustment. If this were done just for the extreme climatic events, and if we acted upon what we already know, as is being done in some places, we estimate that the world death toll from flood, drought and tropical cyclones could be reduced by 85 per cent and the property damage by 50 per cent /5/.

We must emphasize, however, that this is no small or unchallenging task. It is not a task to be relegated to an "information applications office" or to the production of a set of accurate but sterile handbooks, such as can be found in the synthesis of agrometeorological data. Rather, it involves basic research into such varied processes as the perception of threat, the dissemination of warnings, the use of environmental data in the planning and the design of human settlements.

3.2 The challenge of climatic impact analysis

This Conference has many remarkable qualities, not the least of which is the initiative of the WMO and the organizers to extend the welcoming hand of collegiality to those of us in the human sciences and to propose a partnership for the joint solution of one of the potentially great questions of the human environment. Such

initiatives are unfortunately rare in the house of science, and the atmospheric science community is again providing leadership for scientific co-operation between disciplines as it earlier provided leadership for international co-operation within its discipline.

It is easier, however, to invite a guest than to make him or her welcome, and easier yet than to share one's home. Considerable patience will be required to consummate this partnership, and such patience might be encouraged by recognizing one great similarity and one great difference between the geophysical and human sciences.

First the similarity: It is common, though somewhat insulting, to use such terms as "hard" and "soft" science to describe differences between physical and social science, and one is struck by how difficult it would be to apply such terms generically in the context of our common subject - climate. Indeed, in a very real sense there is a convergence of our common scientific problems.

Earlier I singled out three scientific problems that we scientists of society face in understanding climatic impacts: the absence of an accepted theory of social development; the failure to understand the effect of perturbations on complex social systems; and our limited knowledge of human perception and behaviour in the face of slow, pervasive, but cumulative change. However, after a week of listening to the disarray of the atmospheric theory of forcing mechanisms, to the debate over the so-called "robustness" of the atmospheric system, and to the confusion of how to recognize the signals of slow, pervasive cumulative climate change, I do not feel "soft" at all. Some of our understanding seems to be considerably harder than that of the physical scientists. For example, we understand the human causes of desertification better than the atmospheric causes /6/, and we have clearly identified a number of positive feedback loops that make things worse when one tries to make them better /5/.

One must now have a strong awareness of the similarity of our problems, of the real challenge we share in understanding and acting upon climatic impacts. In the past this convergence has not been clearly recognized. Geophysical scientists expected and received from social and behavioural scientists highly simplified and relatively uninteresting attempts at impact analysis based on simple stimulus-response, deterministic, one-impact-parameter models drawing on weak correlations. No basic research effort to encourage and support impact assessment was developed, there were no observational networks put in place and there was no mobilization of resources. In many instances "impact assessors" were either viewed as helpful technicians or entertaining lunch partners but not as serious scientific collaborators. The impact assessment phase of the World Climate Programme will fail unless it is acknowledged that the problems are of wide scope, and that numerous disciplines including the human and physical sciences must converge and collaborate for their solution.

Let us recognize that the differences between our disciplines may raise difficulties over collaboration even in matters of common interest and responsibility. There is no straightforward disciplinary and institutional development of economists, political scientists, psychologists, and sociologists interested in questions of climate. Only "human geographers" have some basic disciplinary encouragement in that direction - that is why we are so well represented at this Conference. Indeed, the disciplinary structures of most of the social and behavioural sciences serve to draw

them away from an involvement in climate impact studies. Thus a special effort will have to be made to create new incentives for attracting and holding the interest of bright social and behavioural scientists. For many of us here, whose lives revolve around understanding the oceans of air and water, it is difficult to imagine a partnership with those for whom the interest is at best peripheral. We will have to move towards the creation of a human-oriented atmospheric science if our programme is to succeed.

3.3 Climate choice as evaluative judgement

Finally, I wish to dispose of a certain fallacy before we enshrine it as a myth. Implicitly, and occasionally explicitly, the suggestion has been made here that the end result of a world climate programme would be to have such scientific understanding of climatic change, variation, and impact that rational, objective decisions can be made. We actually know a great deal about decision-making, and what we know does not suggest that this simple view, often labeled as the "economic" or "expected utility" model, will prevail /19/. The great choices that our emerging climatic understanding will pose will always be made under conditions of uncertainty. They will be made in the face of conflicting information by nations and individuals with conflicting goals. In the face of such uncertainty choices that depend on climate will be evaluative rather than cognitive, and we would be well-advised to consider such value judgements directly.

For a long time to come our understanding of the benefits and costs of various choices will, of necessity, be clouded and limited. Are there any transcendent, overriding values that should not be determined by standards of efficiency? Let me suggest one for discussion.

In a world where we can fashion Concordes and Tupelevs, spray cans and military weapons, minimum security from disaster should be a human right. The last great subsistence crisis in the Western World took place in 1816 /20/; no one dies of drought today in dry Australia /21/; and upwards of a million people are now routinely evacuated in the coastal plains of the United States /22/. There is much in nature beyond our control, but the death rate from climatic disaster can be drastically lowered. There is no rational calculus that will demonstrate the value of the 150 000 Bangladeshis that might have been saved in 1970, or of the tens of thousands in Ethiopia in 1972. There is only a powerful moral value that declares that if such deaths are unnecessary and preventable then they are unacceptable.

Currently we have no completely rational or objective way to foresee the future, yet for a week we have discussed the climatic impacts of the year 2000, or 2050, or even 2400. Proper economic analysis always discounts the future against the present, and even at the smallest reasonable discount rate the future quickly becomes valueless. But fortunately we do not behave as if we believed in such analysis. The concern for future generations (as well as for ancestors) is a part of our common human heritage. How to assert this value, how to recognize it in a rational calculus that denies it, is a troubling and vexing issue.

Finally, perhaps the most troubling of all to incorporate into our analysis is our ambivalence towards nature, to love it and reject it, to know it and control it. If it will be shown that our burning of fossil fuel will, in the course of a handful of generations, create a climate unknown for the last two million years of existence, can we change that climate with moral impunity? Whether nature is "robust" or not, are there no constraints other than practical considerations to our right thus to perturb our environment?

There is a healthy dialectic between fact and value. It is to be hoped that fact will inform our values and narrow the dilemma of our choices. But in the years ahead, of trying and difficult research, of confusing international and interdisciplinary collaboration, of fluctuations in the support and attention our programme will receive, it will be our values, our common outrage at needless death and destruction, our common concern for the future and for future generations, and our common love for the nature we struggle to understand, that will bring us together, that will keep us together, and that will carry forward this programme.

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REPORT ON DISCUSSIONS HELD DURING THE FIRST
WEEK OF THE CONFERENCE

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1. INTRODUCTION

The programme for the Conference is reproduced in Appendix A where it will be seen that for purposes of presentation during the first week the overview papers were divided into a number of groups according to their subject. This step was necessary in the interests of organization but there was no intention in that procedure to restrict the area of discussion at any of the sessions. Indeed it was appropriate for discussion to range freely at each session since, in the broad context of world climate, it might be said that the papers were all interrelated in ways which cut across any sub-division of the subject as a whole. For this reason the following summary of the discussions does not deal with each session separately but is an integrated report covering all the sessions.

Since the papers themselves appear elsewhere in this volume, it is unnecessary to recapitulate their contents here except when it is desirable to provide background to any of the points that were raised. For the most part, the aim has been to cover the main issues that were debated from the floor. In some cases, of course, it was these particular issues that formed the reason for convening the Conference and they were discussed at greater length in the ensuing week during the meetings of the working groups.

In the space available it is not possible to quote the many perceptive comments that were made during the discussions or to give the supporting arguments in detail. However, these notes may serve as a reminder to those who participated and they may also be of interest and value to others reading the papers for the first time.

2. SUMMARY OF DISCUSSIONS

2.1 Physical basis of climate - climate modelling

Considerable interest was shown in the problems and uncertainties of giving an adequate description of the climatic system with its five physical components - the atmosphere, oceans (hydrosphere), ice-masses (cryosphere), land (lithosphere) and biosphere. Apart from the atmosphere itself, which shows the greatest variability on most spatial and temporal scales, the role of the oceans was most prominent in discussion. Concern was expressed at the limited amount of oceanographic data available. Meteorologists and oceanographers in their studies of climate need data for various levels of the ocean, not merely at the sea surface, and it was suggested that full support should be given to oceanographers who are already pressing for the establishment of special observing networks for ocean data. The oceanographers present stressed that this would be an extremely difficult and expensive undertaking.

Good progress had been made in the development of general circulation models (GCM's) for simulating major features of the global atmospheric circulation and of the average state of the present world climate. However, even the more advanced models do not give predictions of changes in average climate over a year or decade or from, say, one winter to the next. On the other hand, the models have been used with some success to investigate the response of the climate system to specified natural changes, e.g., in the sun's radiation, and to possible man-made changes, e.g., in the land surface or in the carbon dioxide content of the atmosphere.

A crucial question that was debated was the reliability of the models in simulating the response, or "sensitivity", of the climate system to such induced changes. One body of opinion felt that great caution should be exercised in assessing the model experiments which showed the theoretical response of the climate to a doubling of carbon dioxide in the atmosphere. It was argued that there could be some important feedback mechanisms, such as cloudiness or changes in ocean circulations, which were not adequately treated in the models. A consensus seemed to emerge, however, to the effect that, in spite of the extensive simplifications of the models, they were probably approximating the correct sensitivity fairly well.

The need for more refined models able to display the response of the climate on a regional scale was repeatedly emphasized. Changes to be expected in both temperature and precipitation distributions must be known on this scale if the results are to be of use to planners at the national level.

During the course of the discussion, reference was made to the "robustness" of the climate system, in other words to the extent to which strong feedbacks could preserve its stability in the face of forced changes. The concept was challenged in the light of paleoclimatic evidence for large and occasionally sudden shifts of climate although the causes are unclear. Furthermore, it was argued on theoretical grounds that a complex, non-linear system could have more than one quasi-stable state and could quite suddenly change from one to another. It was pointed out, however, that if the climate system does possess any actual instabilities, they are extremely difficult to detect. Indeed, it was noted that climate models do exhibit a degree of stability or "robustness" when boundary conditions are changed.

2.2 Some aspects of climatic variability

The variability of climate on all time scales and the tendency of the atmosphere to return to a state not very different from its long-term average condition are both well known. Climatic variability is one of the key influences on the human economy, the main impacts being caused less by long-term changes than by short period anomalies of precipitation or temperature. It was suggested that the high variability of temperature and of precipitation during the 1970's was probably not abnormal but the effects were highly significant because cereal growing regions and major pastoral belts were affected. Strong doubts were expressed about statements, frequently made, that the past decade had seen an increase in variability in world climate.

In recent decades the trend of atmospheric and sea-surface temperatures appears to have been downward in the northern hemisphere and slightly upward in the southern hemisphere. The evidence for such a trend is not clear cut, however, and it

is stressed that great care is needed in the statistical interpretation of climatic data since aggregated figures could be misleading. On a global and annual basis it was difficult to confirm any recent temperature trend one way or the other, but analysis of recent northern hemisphere data by seasons indicated warmer springs and autumns, effects which might be the origin of the current glacier recession.

Much attention was given to the possibility of making useful extended range weather forecasts giving trends and variations from the climatic norms for up to a year ahead. Several of the overview papers touched on this question. Methods of attack have involved the identification of periodicities in the weather and the assumption that such periodic behaviour would be maintained, and also a variety of techniques based on the view that prolonged changes in sea-surface temperature or snow and ice cover would affect the large scale circulation in a manner that could be specified. The discussion was notable for both lively interest and the reservations expressed. Interest was aroused by the obvious value of monthly, seasonal or longer-term forecasts of climate variations. Reservations were based, at least in part, on the theoretical contention that short-lived quasi-random weather systems create a "noise" that tends to mask any longer term "signal" as might be given, for example, by an ocean temperature anomaly. It was also remarked that the periodicities that could be used for seasonal forecasts appeared to have small amplitudes and would therefore not be expected to give much forecast skill in the statistical sense.

2.3 Climate scenarios

A climate scenario was seen to be a flexible means of assessing the properties of climates under conditions that have occurred in the past or seem likely to occur at some future time. The climate in question is presumably a realistic one although it may not be possible to describe how it evolved in the case of an earlier climate or how it would develop to its assumed state in the case of a future climate.

A technique of climate reconstruction is provided by paleoclimatology, the science of climates of past geological epochs. It was explained that this subject has broadened in scope and capability as geochemical techniques, mainly based on isotopes, have rapidly expanded the volume of information available about past climates, yielding absolute age datings and paleotemperatures.

A study of warm and cold episodes in climate history shows the different effects likely to result from natural causes. For example, global cooling could result from a sequence of heavy volcanic eruptions which would infuse dust into the stratosphere and disturb the radiation balance; on the other hand, global warming could be caused by a lull in volcanic activity or by an increase in the concentration of carbon dioxide in the atmosphere from any source.

Studies on these lines help in the construction of climate scenarios and, as the discussion showed, the scenario method can be used with climate models and indeed illustrates their versatility. Some of the most challenging scenarios are those concerned with the possible effects of man's activities on the climate. The models also give an insight into climate-forming factors and are being used experimentally in the construction of past climates and have also been adopted as a tool in paleoclimatology.

The value of scenarios, whether to describe past climate or for projections into the future, was well recognized. It was emphasized, however, that because boundary conditions and the composition of the atmosphere undergo changes, paleoclimatology on its own can hardly be used as a basis for climate prediction.

The scenario method has clearly helped to draw attention to the probability of a gradual global warming around the turn of the century. Even though past climates should be used with caution in estimating future climates, an interesting and suggestive example which was mentioned was the Late Tertiary (about 12 to 2.5 million years ago) with a fully glaciated Antarctic and a virtually ice-free Arctic Ocean having a marked influence on the atmospheric and oceanic circulations. It appeared that if the concentration of atmospheric CO₂ were to rise above a certain level, there would be an increase in the probability of global warming to an extent that could cause the thin arctic pack-ice to disappear.

2.4 Climate monitoring and data collection

There was no question as to the vital necessity of establishing adequate services responsible for climate monitoring and the collection of climatic data. The whole range of data requirements is vast, comprising meteorological, oceanographic, hydrological and geophysical data in one category and biological/ecological data and sociological/economic data in other categories. It was noted that well established data bases already exist in the form, for example, of the WMO programme of World Weather Watch (WWW) and in special climatological networks set up by national meteorological and allied services. However, there is a need for the expansion of existing facilities and for the creation of new networks in order to cover all the requirements of a climate monitoring programme.

Considerable concern was shown about the lack of data from ocean areas, in particular from those areas where time and space variability of temperature are relatively large. There was considerable anxiety on the need to improve the quality of such ocean data as are available at present and it was pointed out that the standard error of sea-surface temperature measurements is unacceptably high.

Monitoring climatic change and variability raises many interesting questions, some concerned with definitions and others with the relative importance of different types of variability. It was suggested that changes in inter-annual variability could be as important as a trend in mean temperature, and the problem of identifying systematic trends was also discussed. The influence of the oceans in reducing climatic variability was mentioned as another important argument in favour of monitoring the oceans.

2.5 Climate and the biosphere

The biosphere is one of the five components of the climatic system and interacts with the other components primarily on time scales which are characteristic of the life cycles of the earth's vegetative cover. The most prominent cycle is that of the plant growth in response to the seasonal variations of solar radiation, temperature and rainfall. Many of man's activities have significantly altered the earth's

vegetative cover and thus interfered with the natural biospheric component of climate. Man's land clearing and agricultural activities over thousands of years may have had a greater influence upon climate than the more recent growth of industrial activity. At the same time it was noted that the features of the earth's ecosystem are determined to a considerable degree by the climate.

It was suggested that major importance should be attached to the global biogeochemical cycles of the main elements present in organic matter, namely, carbon, nitrogen, phosphorus and sulphur and, of course, the hydrological cycle. The linkage between these cycles and their possible effects enters into the discussion of most if not all aspects of climatic change. Furthermore, as man is already modifying these cycles, especially as a result of the rapidly increasing use of fossil fuels, it seems essential to monitor and account for any changes that seem likely to occur.

Some of the advantages of an improved understanding of the biosphere were pointed out. If, for example, the biological processes of nitrogen fixation were substantially exploited, it would be possible to limit the production of nitrogen fertilizers the manufacture of which involves the consumption of non-renewable natural resources.

2.6 Climate and the composition of the atmosphere

Within the context of climatic change and variability many participants appeared to regard the most important of man's activities to be those which change the concentrations of certain gases and particles in the atmosphere. These concentrations are modified by the emission of gases and particles from towns and industrial areas and by agricultural activities such as the burning of trees and stubble. The resulting changes in chemical composition of the atmosphere affect the radiation balance, alter the stratospheric ozone budget and, in the case of particles, modify cloud and precipitation processes.

Considerable attention was focused on the emission to the atmosphere of carbon dioxide by mankind. This emission is mostly from the combustion of fossil fuels, though cutting down of forests also releases CO₂ as the organic matter decays or is burnt as fuel. Forests are also a sink for CO₂, making deforestation a further possible contributor to the observed CO₂ increase in the past several decades. However, it was stressed that reliable information about the rate of deforestation in the tropics still does not exist. The climatic effects of CO₂ are brought about by the "greenhouse effect", that is, the absorption of infrared (heat) radiation, which leads to a global warming of the lower atmosphere. Several other infrared absorbing gases also released to the atmosphere as a result of human activities behave in a manner similar to CO₂.

The increasing concentrations of the greenhouse gases like CO₂, of gases which might affect the ozone layer, and of aerosols led to an additional emphasis being placed upon monitoring of atmospheric composition in order to keep touch with changes that were actually taking place. It was also noted that, as the build-up of concentrations could be slow, estimates based on climate model experiments could give timely indications of probable changes which could subsequently be checked by monitoring.

In discussion of possible climatic impacts resulting from increased CO₂ concentrations, the remark was made that variations in temperature and precipitation régimes would benefit some agricultural areas and raise problems in others. It would be necessary to devise international measures to make good use of the increased crop yields in order to aid those countries where crops had been reduced.

Since the effects of increasing CO₂ concentrations would be on a global scale, it was evident that any plan of action to reduce climatic change or to minimize the adverse effects of any changes would have to be organized internationally. For example, action by a few nations to restrict the use of fossil fuel would probably have little effect. World wide agreement and compliance would be essential.

2.7 Energy and climate

Climate influences the demand for energy; the by-products of the production and consumption of energy can influence climate. The discussion, of this topic was introduced by a 50-year projection to the year 2030 when, it was claimed, the population of the world would have doubled its present size, the consumption of energy would have increased fourfold (or more) and the requirement for food would have trebled. It might by that time have become necessary to use all available energy sources including, besides fossil fuels, nuclear power stations, solar thermal electric conversion (STEC) and ocean thermal electric conversion (OTEC). Nuclear fusion was not considered for this time frame. Many possibilities were noted for reducing the anticipated fourfold increase of energy demand, particularly by means of improvements in the construction and insulation of buildings. It was noted that the capital investment that would be required for such a major growth of energy generating facilities might not be made available and this would result in a slower growth of energy demand and use in some sectors.

The consumption of energy involves the release of waste heat to the atmosphere. However, it was considered that such emissions would have virtually no global effects on climate although local and regional effects are already noticeable and might be increasingly important. Effects on local climate could also result from the reservoirs built for hydro-power generators since that would cause changes in the surface albedo.

Interest was shown in STEC and OTEC systems which have the potential to supply large quantities of energy as an alternative to the use of fossil fuels. It appears that these systems, depending on their size, could have significant local impacts on climate. Some doubts were expressed about the use of OTEC systems because of possible changes in sea-surface temperature and uncertainties as to the net effects of releasing carbon dioxide from the ocean to the air and as to the potential effects as a consequence of increased phytoplankton production.

These alternative energy sources with their mainly local effects on climate provided an interesting discussion, but it was evident that the greater risk to global climate from energy production at the present time arose from large scale releases of CO₂ to the atmosphere. The problem was seen to be complex, involving the carbon cycle and the long-term use of fossil fuels in the future. No conclusions could yet be made

available that would enable informed decisions to be made on energy production and future use of fossil fuels. In any event there was still room for debate as to the balance between the beneficial and the detrimental effects of increased CO₂ in the atmosphere. Agricultural production would almost certainly be enhanced provided other factors were not limiting.

It was appreciated that long lead times are required for the construction of major energy generating plants and there was considerable emphasis therefore on the need to undertake long-term planning of energy production. Much work remained to be done in both theoretical and applied research so that energy policies could be given a better foundation in relation to energy-climate interactions. In this connexion reference was made to the WMO Plan of Action in the Field of Energy Problems.

Although the discussion mainly centred on energy production, attention was also drawn to the manner in which climate affects practically all activities associated with energy production. For example, the efficiency of solar or hydro-power production is affected by variations in solar radiation or in streamflow. Energy demand is also very dependent on climatic factors, notably changes in temperature and in increasing radiation.

2.8 Water resources

Considerable interest was shown in the problems of the engineer concerned with water resources who seeks to take climatic variability into account in project design and operation. Since precipitation and evapotranspiration have important effects on streamflow, the planning of water resources is greatly concerned with the climatic characteristics of precipitation, temperature and radiation. Of necessity it is assumed that the statistics derived from measurements over the past 50 to 100 years will be applicable for the next 50 to 100 years. Questions were raised as to the possibility, by climate models or in other ways, of predicting changes in the mean values and variability of the components of the hydrological cycle. It was accepted that such possibilities must be actively pursued in appropriate research programmes since it was not yet possible to provide the climate predictions governing the parameters concerned, especially on a regional scale.

A matter of particular interest and one that was welcomed by meteorologists was the readiness of hydrologists to extend their concern beyond the statistical facts of rainfall and meteorological elements to impinge on certain aspects of the general circulation of the atmosphere. Considering the distribution of water resources as a global problem, it was important to have more information available about the transfer of water vapour from the southern to the northern hemisphere through the agency of the monsoon. It appeared that this problem could be tackled by the further development of global circulation models, and note was taken of the GARP Monsoon Experiment (MONEX) whose first phase was under way at the time of the Conference.

In the discussions various subjects of the widest scope were recognized including such possible developments as the coupling of climate and hydrologic models and their extension to incorporate social and economic factors.

2.9 Climate and health

The discussion brought out in a striking way the problems that whole communities would face in the event of significant changes in their climates. For example, if the climate in a region changed and became more tropical, a variety of new diseases could occur to which the local population had developed no immunity or other defences. The question of migration might have to be considered.

To a great extent man controls his environment by wearing suitable clothing and constructing climate-controlled buildings. By such means he is able to survive a wide range of climatic conditions. Nevertheless, man has shown a preference for living in areas where the climate is free from extremes of temperature and of other conditions which affect the body's heat balance.

The seasonal feature of mortality rates was discussed and it was noted that in developed countries there had been a marked reduction in the amplitude of the fluctuations that occur and, as a result of changes in the causes of death, there have been some major shifts in the times of maximum mortality.

The strong influence of climate on insect-borne diseases was considered to be a factor of special importance in tropical regions where many developing countries are to be found and where malnutrition reflects another of the serious impacts of climate on human health. Predictions of climatic variations or anomalies, or even medium-term forecasts of weather conditions, could help in preventing outbreaks of disease among both human beings and animals.

It was clear that climate has an important bearing on numerous problems concerning health and disease. Man may be able to lessen the impact of small climatic changes on his well-being but any changes which are particularly severe or abrupt could have serious consequences, and the aim must be to foresee such changes in climate in good time.

2.10 Climatological aspects of agriculture

The importance attached to the effects of climate change and climate variability on agriculture was shown by the allocation of two whole sessions and a major part of a third session to this wide subject. The overview papers dealt with global food production, land-use in Africa and the effects of climatic variability on agriculture in temperature regions, the semi-arid tropics, the tropical moist regions, Latin America and China. The importance of these subjects was marked by the interest shown and by the quality and range of the discussions that took place.

Meteorologists who specialize in the problems of agriculture supported the requirement for continued basic research into climate but stressed the importance of making full use of presently available knowledge of climate in the planning and day-to-day operations of agricultural activities. Many participants claimed that a wealth of valuable climatological information already existed but was not being supplied to agriculturists and planners. It was pointed out that of all climatic impacts the impact on agriculture was probably best appreciated, and so there were vast opportunities to exploit climatological data tailored to meet specific requirements.

Some participants described progress made in agroclimatology in their own countries and mentioned the preparation of maps and handbooks and the development of methods for forecasting crop yields and for assessing the over-wintering effects on crops. A relatively new facet of agrometeorology and one with tremendous potential was crop-weather modelling. Some participants referred to the resilience of agriculture, pointing to its ability to recover from adverse climatic events, but this resilience was said to be strongest in a mixed agricultural system.

A question was asked as to the role of FAO in eradicating famine and malnutrition. It was explained that famine was a long standing preoccupation of FAO and a number of measures had been taken in the past decade to develop food security schemes. The Global Early Warning System, which was supported by nearly 100 countries, had been introduced in order to collect and disseminate information concerning possible crop failures.

On the subject of world food supplies it was pointed out that the world could produce sufficient food to feed its growing population provided that required efforts were made in terms of manpower, energy and the employment of modern techniques. This course was being followed in the U.S.A., U.S.S.R. and, more recently, being done in India - other countries might follow their example in certain cases.

Agriculturalists in the audience appealed for more weather information from the meteorologists, emphasizing that agroclimatological studies should take plant and soil factors into account as well as meteorological factors. It was stated that farmers and agriculturalists generally would welcome guidance on the ways in which agricultural practices could cause changes in climate, e.g., the effects of extensive irrigation on both local and regional climates. The feeling was expressed that very often the increased use of nitrogen fertilizer was wrongly given as the cause of the increase in nitrous oxide in the atmosphere (one of the greenhouse gases); this increase was also contributed to by natural sources and organic manures as well as by industrial and domestic activity. Agricultural research would improve the efficiency of nitrogen fertilizers leading to reduced quantities; this should be taken into account in modelling and extrapolating for the future. The agricultural industry was vitally interested in climatic research and would support it.

Various suggestions were made regarding possible avenues of agro-climate research. Long records of weather, such as those available in China, were most valuable in investigating the existence of weather cycles. On the question of cycles, reference was made to the work being carried out in Japan on investigating the Brückner solar cycle; this work had shown some promising results. As regards the supply of agroclimatological information to users, it was agreed that, apart from presenting this information as a comprehensive "package" (means, variabilities, probabilities, confidence limits), it was necessary to include all the relevant parameters; in this connexion, it was pointed out that the humidity factor did not always receive the attention it merited since it was very important in the fields of plant disease, photosynthesis, evapotranspiration, storage of products and animal stress.

An important comment drew attention to the fact that none of the agricultural papers had dealt with pests and diseases, a surprising omission considering that the effects of climatic variability on them, as affecting the ultimate production, are no less significant than on the plants themselves. In a number of countries the climatic conditions which favour increased wheat yields also favour rust development which has adverse effects on yields.

It was argued strongly that the problem of climatic variability in the tropics should be tackled more vigorously and aimed not only at providing sufficient food but also at realizing surpluses to act as a cushion during the lean years.

With regard to land use in Africa, some surprise was expressed at the statement that rainfall was the major, perhaps the only, important climatic parameter. It was shown, however, that studies of rainfall fluctuations had been used to explain the agricultural history in Africa for many years past. It was also explained that in the agricultural system, including long-term projects, full advantage is taken of information on climatic variability which is used, for example, in the selection of crops for particular areas.

As a general comment on the discussion as a whole, it may be remarked that agricultural systems, which include cultivation, harvesting, storage, marketing and other facets, appear to be remarkably flexible and efficient. It may also be mentioned that agroclimatologists seemed to be much more concerned with extended range weather forecasts and climatic variability than with climatic change.

2.11 Soil science

During the discussions on agricultural topics, a participant intervened to explain the importance of soil science in connexion with climatic variability. Soil characteristics show a strong dependence on climatic elements and some interesting facts with regard to population density and land use were described.

In Africa the regions with the highest density of agrarian population and the largest acreage in use lie within the semi-arid dry savanna belt near the northern dry limit of rainfed cultivation. In the humid inter-tropical zone the density of agricultural population and the intensity of land use are several times lower. Nevertheless, elsewhere there are some extremely densely populated agrarian areas of limited size within the generally less populated humid tropics. For example, Java is very densely populated compared with the neighbouring islands of Indonesia.

These features of population distribution suggest that natural factors besides climate may have an important role and the importance of soils should be recognized. Soils have strong regional and local variability depending on petrographic, topographic and drainage conditions and also exhibit the strong influence of climate, particularly on soil characteristics which play an ecologically decisive role. One of these characteristics is the cation-exchange capacity which determines the response of different soils to fertilizers. Weathering processes can cause a low exchange capacity. Semi-arid tropical areas like the Sahel have soils with a relatively high exchange capacity. It was argued, therefore, that the findings of soil science should be taken into account in considering the influence of climate on food production in tropical regions.

2.12 Forests and climate

Forests were referred to frequently during several of the sessions especially when concentrations of carbon dioxide in the atmosphere were being discussed. Forests have a valuable role in removing CO₂ from the atmosphere and anxiety was shown about reports that whilst forests are being cleared by man there are few signs of planned or natural re-forestation.

It was also pointed out in discussions of land use that deforestation causes an increase in the albedo and has an effect on the radiation balance.

As with many activities associated with climate, the interactions between forest and climate go both ways - forests are affected by fluctuations in climate and the climate is affected by changes in the forest cover.

The importance of forests to global climate was widely accepted but some participants also emphasized the significance of forests to climate on a local or regional scale. For example, in human settlements in the tropics forests have a valuable effect in moderating the hot environment. In another comment it was noted that the effects of the rapid deforestation which has occurred in recent years were not yet adequately appreciated. It was hoped that the Conference would record the view that in forestry mankind has a tool to control regional climates and that in all regional planning the climatic aspects of changes in land use should be fully considered.

The importance of forests to macro-scale ecology was also brought out, in particular their value in safeguarding water and biochemical balances. There appeared to be no difficulty in accepting statements that the total area of forest should not be diminished to any great extent before enough knowledge is available to assess what the consequences would be to regional and global climates. If climatic changes and fluctuations have to be offset or balanced, a good regional distribution of forests would be of great value. The political and economic problems that would be encountered in achieving such a distribution would be very great, however.

2.13 Fisheries and climate

Fishermen are well aware that the weather affects fishing and that the climate has a marked effect upon fish populations. However, the influence of climate upon the rise and decline of fish populations was said to be more complex than had been considered previously. To some extent fish can escape unfavourable conditions but have to find alternative areas with adequate supplies of phytoplankton and biomass.

Questions were raised as to whether climatic influences were seriously masked by commercial practices such as over-fishing. It was agreed that these difficulties could arise but research into the effects of climatic variability concentrated on case studies in which the different factors could be separated.

2.14 Offshore developments - oil drilling

Due emphasis was given to the importance of a knowledge of climate and of possible changes in climate in all planning for the extraction of marine resources from the sea bed. However, the main interest in the discussion was shown in the possibilities that oil spills and oil pollution could affect climate. It was explained that any such effects would be negligible. Thin oil films would have practically no effect on evaporation, albedo or drag coefficient. As for thick films, they are of local occurrence and their lifetime limited.

However, it was stressed that, although oil pollution may be of no consequence in regard to climatic change, it is a highly important and undesirable factor in marine ecology.

2.15 Economic and social aspects

Efforts to describe and quantify the impacts of climatic change upon economic and social activities gave rise to a discussion of outstanding interest. From some meteorologists there was very strong technical criticism of the assumptions made by economists and of the statistical methods that were employed. It was asserted that the results, as presented, must have large uncertainties. It was also mentioned, however, that meteorologists themselves are no strangers to questionable assumptions and do not shrink from practical problems of such complexity that confidence in the results obtained has to be heavily qualified.

On the whole there was a general welcoming of pioneering efforts to quantify the economic impacts of climatic change and, as the data and statistical analyses had been published, opportunities were available to examine the methods employed and to improve and extend them.

It was noted that the costs or benefits of climate variability fall inequitably upon different social or economic sectors of society. It would be a difficult problem to restore equity and it was suggested that a practical approach might be to try to identify, region by region, those who had gained and those who had lost as a result of a particular change in climate. Decisions would then be required as to how far those who gained should assist in compensating the losers. Another major difficulty in cost/benefit analyses would lie in assigning a value to human life. It was customary to deal with the question indirectly, i.e., by trying to assess the various probabilities and then considering the costs of avoiding the extra risks to the populations arising from a climatic change.

In a comment on estimates of the economic costs of a 1°C global average temperature change, a question was raised as to whether the overall economic effect of an actual climatic variation in the past had been considered. In another question it was commented that no known climatic change had resulted in all parts of the world warming or cooling equally, and in most known cases some regions became cooler when others became warmer.

It was mentioned that earlier theoretical work in social and economic development took little or no account of climatic change, presumably because it was believed that the climate was unchanging. In recent years, however, there had been increasing attempts to take the environment into account in socio-economic studies. It was recognized that such studies could present policy makers with a number of alternative courses of which few would be free from potential regional or class conflict. Governments, when faced with specific choices, should be seen to have the best available information and advice. It was therefore suggested that there would be advantages, particularly in regard to objectivity, if these studies were internationally organized.

An interesting point of discussion was that in several overview papers concerned with widely different aspects of climatic change, the conclusion had been reached that there was no immediate need for regulating human activities in order to avoid adverse effects on climate. That an economic study had arrived at a similar conclusion was clearly of special interest.

There was also good discussion on the long-term human response to recurring phenomena which may cause disasters, e.g., droughts, floods, tropical cyclones and tornadoes. Extreme events of this nature are features of the climate and should be taken into account in appropriate regional and national planning. Every effort should be made to minimize loss of life but, in regard to industrial and other damage, it should be appreciated that ambitious attempts to mitigate natural disasters may not prove to be the best strategy. In some situations a community might fare better by accepting a rare loss than by diverting scarce resources in order to prevent its recurrence.

3. REVIEW

The presentation of papers and the discussions during the first week of the Conference formed a preparatory stage for the meetings of the working groups and the formulation of the Conference Declaration in the course of the second week. It would be inappropriate, therefore, to draw conclusions from the proceedings of the first week and so it may suffice to draw attention to some aspects of topics which the participants appeared to regard as of major concern.

Progress in modelling the climate system may perhaps be described as modest but encouraging. The complexity of the problem is probably unparalleled. Research is proceeding into certain important interactions among components of the climate system but it is likely that there are other interactions or feedbacks which have still to be identified and their importance assessed.

A number of models may be used to obtain fairly realistic assessments (perhaps within a factor of about 2) of the influences on global climate of increased concentrations of carbon dioxide and other greenhouse gases in the atmosphere. This is a matter of exceptional importance because it is known that CO₂ concentrations have increased and will undoubtedly continue to increase. As Gates says in his paper, "if man's increasing alteration of the environment results in the introduction of previously unknown influences on the climate, the modelling approach is the only method which can be used to predict the future course of climate".

This type of consideration emphasizes the importance of both monitoring the climate system and climate modelling, which must be pursued together. One of the most important objectives of monitoring should be the identification of those natural and man-made influences on the climate which might seriously affect the biosphere and human society. This objective would be an essential preliminary step in considering the measures to be taken in order to plan for and possibly prevent undesirable climatic changes.

Since so many of the activities that may influence climate are related to the production and use of energy in one way or another, it is clear that future energy policies - the choice of energy strategies - are closely linked to the question of climatic change. It was emphasized repeatedly that, in order to be meaningful, these problems should be approached internationally and on a global scale.

Agriculture is probably the sector of the economy which makes the greatest use of information on weather and climate. Clearly full weight should be given to the requirements of agriculture and it appeared that climatic variability, as revealed in differences between one year and another or one season and another, was of greater concern than long term climatic change. This is a valuable guide to the most urgent requirements of agriculture, and much interest was shown in the statements that significant progress had been made in preparing weather forecasts for a season and up to a year ahead. On the other hand several meteorologists expressed reservations about current ability to make seasonal (or longer) forecasts and suggested that one should not promise too much until success had been more convincingly demonstrated.

Finally, several of the overview speakers and those commenting from the floor noted that this Conference was remarkable for the breadth and depth of its subject matter. The problems and challenges associated with the impacts of climate variability and change on society will continue to demand an interdisciplinary approach; and it was emphasized that new ways must be found to encourage such research and the training of a generation of scientists capable of working at the interface between the physical and social sciences.

THE DECLARATION OF THE WORLD CLIMATE CONFERENCE

Preamble

The World Climate Conference, a conference of experts on climate and mankind, held in Geneva from 12 to 23 February 1979, was sponsored by the World Meteorological Organization in collaboration with other international bodies.

The specialists from many disciplines assembled for the Conference expressed their views concerning climatic variability and change and the implications for the world community. On the basis of their deliberations they adopted "The Declaration of the World Climate Conference", the text of which follows.

The declaration was based on supporting documents proposed by the working groups of the Conference. These documents therefore constitute valuable background information to the declaration and are also reproduced in this publication.

* * *

An Appeal to Nations

Having regard to the all-pervading influence of climate on human society and on many fields of human activity and endeavour, the Conference finds that it is now urgently necessary for the nations of the world:

- (a) To take full advantage of man's present knowledge of climate;
- (b) To take steps to improve significantly that knowledge;
- (c) To foresee and to prevent potential man-made changes in climate that might be adverse to the well-being of humanity.

* * *

The problem

The global climate has varied slowly over past millennia, centuries and decades and will vary in the future. Mankind takes advantage of favourable climate, but is also vulnerable to changes and variations of climate and to the occurrence of extreme events such as droughts and floods. Food, water, energy, shelter, and health are all aspects of human life that depend critically on climate. Recent grain harvest failures and the serious decline in some fisheries emphasize this vulnerability. Even normal variations and modest changes relative to the normal climate have a significant influence upon man's activities.

All countries are vulnerable to climatic variations, and developing countries, especially those in arid, semi-arid, or high rainfall regions, are particularly so. On the other hand, unfavourable impacts may be mitigated and positive benefits may be gained from use of available climate knowledge.

The climates of the countries of the world are interdependent. For this reason, and in view of the increasing demand for resources by the growing world population that strives for improved living conditions, there is an urgent need for the development of a common global strategy for a greater understanding and a rational use of climate.

Man today inadvertently modifies climate on a local scale and to a limited extent on a regional scale. There is serious concern that the continued expansion of man's activities on earth may cause significant extended regional and even global

changes of climate. This possibility adds further urgency to the need for global co-operation to explore the possible future course of global climate and to take this new understanding into account in planning for the future development of human society.

Climate and the future

Climate will continue to vary and to change due to natural causes. The slow cooling trend in parts of the northern hemisphere during the last few decades is similar to others of natural origin in the past, and thus whether it will continue or not is unknown.

Research is revealing many basic features of climatic changes of the past and is providing the basis for projections of future climate. The causes of climate variations are becoming better understood, but uncertainty exists about many of them and their relative importance.

Nevertheless, we can say with some confidence that the burning of fossil fuels, deforestation, and changes of land use have increased the amount of carbon dioxide in the atmosphere by about 15 per cent during the last century and it is at present increasing by about 0.4 per cent per year. It is likely that an increase will continue in the future. Carbon dioxide plays a fundamental role in determining the temperature of the earth's atmosphere, and it appears plausible that an increased amount of carbon dioxide in the atmosphere can contribute to a gradual warming of the lower atmosphere, especially at high latitudes. Patterns of change would be likely to affect the distribution of temperature, rainfall and other meteorological parameters, but the details of the changes are still poorly understood.

It is possible that some effects on a regional and global scale may be detectable before the end of this century and become significant before the middle of the next century. This time scale is similar to that required to redirect, if necessary, the operation of many aspects of the world economy, including agriculture and the production of energy. Since changes in climate may prove to be beneficial in some parts of the world and adverse in others, significant social and technological readjustments may be required.

Increasing energy use and thus release of heat have already caused local climatic changes. In the future such heat sources from densely populated and heavily industrialized regions could possibly have some effects on climate on a larger scale. Other human activities such as agriculture, pastoral practices, deforestation, increased use of nitrogen fertilizers and release of chlorofluoromethanes might have climatic consequences and therefore require careful study. Also, a systematic search for still other possible effects on climate of major human efforts is needed.

Some forms of warfare have local climatic effects. World thermonuclear conflict, besides its catastrophic consequences for mankind, would degrade the natural environment and might cause climatic changes on a large scale.

It is conceivable that in the future man may be able to produce limited changes in climate on a large scale by deliberate intervention. It would be

irresponsible to consider such actions until we have acquired the essential understanding of the mechanisms governing climate that is needed to predict the consequences. Moreover, international agreement must be reached before such projects are implemented.

Conclusions and Recommendations

The World Climate Programme proposed by the World Meteorological Organization deserves the strongest support of all nations

Its main thrusts are:

- Research into the mechanisms of climate in order to clarify the relative roles of natural and anthropogenic influences. This will require the further development of mathematical models which are the tools for simulating and assessing the predictability of the climate system. They will also be used to investigate the sensitivity of climate to possible natural and man-made stimuli such as the release of carbon dioxide and to estimate the climatic response.
- Improving the acquisition and availability of climatic data. The success of the climate programme depends on the development of a vast amount of meteorological, hydrological, oceanographic and other pertinent geophysical data. Furthermore, climatic impact studies and practical application of knowledge of climate by nations in addition requires detailed information about their natural resources and socio-economic structures.
- Application of knowledge of climate in planning, development and management. This effort should include programmes to assist national meteorological and hydrological services to increase the awareness of users of the potential benefits to be gained through the use of climate information, to improve capabilities to provide and disseminate this information, and to facilitate training in nationally significant climate applications. It should include programmes to develop new methodologies for the application of climate data in the food, water, energy and health sectors.
- Study of the impacts of climatic variability and change on human activities and the translation of the findings of such studies in terms of greatest use to governments and the people. This will require improvements in our understanding of the relationships between climate and human society including:
 - (i) The possible range of societal adjustments to climate variations and change;
 - (ii) The characteristics of human societies at different stages of development and in different environments that make them especially vulnerable or resilient in the face of climate variability and change;

- (iii) The means by which human societies can protect against adverse consequences of, and take advantage of the opportunities presented by, climate variations and changes.

The overall purposes of the Programme are thus to provide the means to foresee possible future changes of climate and to aid nations in the application of climatic data and knowledge to the planning and management of all aspects of man's activities. This will require an inter-disciplinary effort of unprecedented scope at the national and international levels.

The conduct of the World Climate Programme involves a broad range of activities and requires leadership and co-ordination among international bodies and close collaboration among nations

It is fully recognized that the international co-operation which is the prerequisite for any world climate programme can only be successfully pursued under conditions of peace.

There is an immediate need for nations to utilize existing knowledge of climate and climatic variations in the planning for social and economic development

In some parts of the world, there is already sufficient information to provide many applied climate services. However, only a start has been made; data and expertise are generally lacking in developing countries. Programmes must be set up to assist them to participate fully in the World Climate Programme through training and the transfer of appropriate methodologies.

* * *

The long-term survival of mankind depends on achieving a harmony between society and nature. The climate is but one characteristic of our natural environment that needs to be wisely utilized. All elements of the environment interact, both locally and remotely. Degradation of the environment in any national or geographical area must be a major concern of society because it may influence climate elsewhere. The nations of the world must work together to preserve the fertility of the soils; to avoid misuse of the world's water resources, forests and rangelands; to arrest desertification; and to lessen pollution of the atmosphere and the oceans. These actions by nations will require great determination and adequate material resources, and they will be meaningful only in a world at peace.

SUPPORTING DOCUMENTS TO THE
DECLARATION OF THE WORLD CLIMATE CONFERENCE

CLIMATE DATA

1. INTRODUCTION

The success of climatic applications, impact studies and research will depend on the development of an adequate, reliable data base.

Climate-related data are required to describe, understand and predict both the behaviour of the climatic system itself, including man's impact on climate, and the relationship of climate to other aspects of the natural world and human society. Data programmes must, therefore, be integrally designed with the programmes for applications, the study of impacts and research. The data base should contain conventional climate data as well as data on climate-related events, and should consist of both conventional climatological data and climate-related geophysical, biological and socio-economic data.

Data are essential for national and world climate programmes, and they should make maximum use of existing facilities such as the World Weather Watch (WWW) and other climate observational and monitoring networks.

2. OBJECTIVES OF CLIMATE MONITORING AND DATA COLLECTION

The establishment of climate monitoring and climate data collection services is necessary for:

- (a) Application of climate data in human activities;
- (b) Assessment of the current global climate condition;
- (c) Scientific research on climate change, climate variability and climate change prediction;
- (d) Study of the impacts of climate variability and changes on human activities.

Different data bases are required to fulfil the above objectives. While the fulfilment of objectives with respect to (b), (c) and partly (d) requires global data, the fulfilment of item (a) requires additional data of national and regional scope. Evidently data bases will overlap. However, the data base for monitoring of climate will serve as a reference set for the climate impact studies and application programmes. The representativeness and resolution of data are determined by the natural variability of the parameters being observed and by procedures for averaging the data.

The data should meet the requirements for the development and testing of models of the general circulation of the atmosphere and oceans and of climate models, and of the needs for various applications.

3. CLIMATE MONITORING

Monitoring of the climate is needed for an understanding of natural climatic change and variability in both space and time and of climate interactions with the biosphere and human activities. In the latter context it contributes information on the important environmental questions concerning possible effects of human activities on the climatic system.

3.1 Types of data

For climate monitoring the following types of data are required:

3.1.1 Primary data

- (a) Surface data from synoptic, climatological and specialized stations (such as radiation stations);
- (b) Upper-air data;
- (c) Data on atmospheric composition and aerosols;
- (d) Oceanographic data, including sea ice;
- (e) Hydrological data, including snow and ice data.

3.1.2 Other geophysical data

- (a) Radiation balance at boundaries of atmosphere;
- (b) Measurement of the "solar constant";
- (c) Data on stratospheric dust load;
- (d) Geomorphological data.

3.1.3 Oceanic data

Air-sea interactions are of great importance in determining climate. Therefore, the first priority should be given to the establishment of monitoring systems in those oceanic regions where the interactions take place most actively.

3.2 Current climate monitoring systems

The following kinds of monitoring activities are already being carried out in the framework of WMO:

- (a) World Weather Watch (WWW);
- (b) World Radiation Network;
- (c) Networks of climatological stations;
- (d) Marine climatological networks;
- (e) World Ozone Network;
- (f) Background Air Pollution Monitoring Network;
- (g) Integrated Global Ocean Station System (IOC/WMO IGOSS).

So far none of the above systems is providing adequate data coverage over the oceans, which occupy three-quarters of the earth's surface. This point is addressed specifically in Section 3.2.2. In addition, data needs and technology (such as satellites) are constantly evolving so that there is always a requirement for reviews of observing programmes, such as will be carried out using data collected during the Global Weather Experiment (FGGE). Further efforts are required for improving satellite observing techniques which, in addition to already developed environmental space observation systems, can be applied to the problem of climate monitoring on a global scale.

3.2.1 The design of climate monitoring systems

For purposes of observing the weather, the WMO initiated and co-ordinates the development of what is probably the largest and most effective environmental monitoring system in the world, namely the World Weather Watch. Although many of the components of this system have been optimized for operational weather forecasting purposes, it already provides an adequate base for many climate-related activities. However, some data (e.g., radiation data) are not provided with sufficient accuracy and density and their observation must be improved.

An essential part of the climate monitoring system is the network of climatological stations, in particular "reference climatological stations". For homogeneity of the data, it is necessary to do more to improve a global network consisting of various types of climatological stations as defined in WMO Technical Regulations. Each type of climatological station should be located in such a way that the influence of local meteorological processes (including those modified by human activities) are suppressed as much as possible. Siting criteria would need to be specified for each type of station, and existing stations that meet the criteria would need to be identified. The criteria for reference climatological stations need not be the same as for air chemistry monitoring systems.

3.2.2 Oceanic observations

It is recognized that a major issue in the process of understanding climate and eventually forecasting climate variations is the problem of the global ocean dynamics. It is essential that the help of the oceanographic community be enlisted to promote the appropriate observational and research programmes on the overall ocean circulation dynamics.

It is also recognized, on the other hand, that air-sea interaction involving the upper layer of the oceans is basic in determining the interannual variability and short time-scale climatic variations. Urgent action must be taken to apply the resources of the oceanographic and meteorological communities to establishing extensive and regular measurements of the upper layer of the global oceans down to the seasonal thermocline. For this purpose, it is recommended that an internationally coordinated, composite observation system be developed with the following components:

- (a) Ocean Weather Stations (as primary reference climatological stations);
- (b) Mobile ships (voluntary observing ship stations);
- (c) Research vessels;
- (d) Satellites;
- (e) Ocean buoys (anchored and drifting).

3.2.3 Multi-media monitoring stations

Proposals have been made for pilot multi-media global environmental monitoring projects which would include monitoring of the atmosphere, the pedosphere, and elements of the biosphere at background monitoring stations. In addition to being cost-effective, such stations would be useful in studies of the biogeochemical cycling of trace substances (particularly carbon, sulphur and nitrogen) and in studies of biospheric response to natural and anthropogenic impacts, including climatic stress.

4. DATA NEEDS FOR RESEARCH, APPLICATIONS, AND IMPACT STUDIES

4.1 Data needs for climatological applications

The scientific basis for applied climatology is well developed, and the data needs are reasonably well defined. (The important work of the WMO Commission for Special Applications of Meteorology and Climatology, and of its predecessor, should be mentioned.)

The data needs for different applications should be discussed and agreed upon between the services which provide data and the users. In addition, the design principles of climatological networks need to be improved.

It should be stressed that the field of applied climatology is continually evolving, presenting new challenges and opportunities. Data needs are changing too, so that periodic reviews of monitoring networks and data archives need to be encouraged (see the Report on Applications of the Knowledge of Climate).

4.2 Data needs for the study of the impacts of climate on human activities

Almost every type of climatic impact study is complex and interdisciplinary. Therefore, impact studies will make extensive use of data relating to other

disciplines. Along with hydrological, meteorological and geophysical information the following kinds of data should be included in the data base:

- (a) Agricultural data;
- (b) Land use inventories;
- (c) Industrial data;
- (d) Ecological data.

The essential part of the data related to these other disciplines should be collected and archived at national archives, and they will probably be used at the national level. Authoritative knowledge of related data sources and archives rests in the United Nations and its specialized agencies, as well as specialized institutions established under the auspices of ICSU. The co-operation of several organizations and national governments may be essential to fulfil the data needs of a major impact study.

What is most important is to develop a data infrastructure such that impact studies can capitalize on much that already exists, and so that entirely new data gathering exercises can be avoided.

4.3 Data needs for research on climatic change and variability

Data for research on climatic change and variability are required:

- (a) To elaborate the comprehensive climate theory;
- (b) To provide data sets for validating and calibrating climate models;
- (c) To provide long time-series of measurements of climate-related parameters of global significance needed for assessment of climate changes and variabilities.

The data requirements in the three cases are quite different (see the Report on Research on Climatic Change and Variability). The collection of a complete set of atmospheric, ocean and land-surface data for the period of at least the last 30 years is the major task.

The FGGE (Global Weather Experiment) data set will provide the most detailed picture to date of one annual cycle, which is of great importance. The assembly of "long-term instrumental record" data sets is also essential. It will be necessary to locate and to assemble instrumental observations made during the last 100 years or more, to examine the data for quality and consistency, and to arrange that the data are readily accessible and suitable for both manual and computer processing.

In general, it is recognized that a variety of additional information will be required for climate research, including particularly:

- (a) Special data sets based on intensive measurements of specific climatic processes for the purpose of parameterization;

- (b) Documentation of past climates, and paleoclimatological records.

4.4 Climatic components of "environmental impact assessments"

Large-scale engineering projects, deforestation (especially in tropical regions), over-grazing and diversion of rivers could also have a potentially important impact on climate. The impact of such activities is to be specially monitored.

5. DATA MANAGEMENT

Data management planning must be an important element of the World Climate Programme.

Large amounts of physical data relevant to the problem of climate have been obtained and are being accumulated in a variety of data banks and archives. However, a large portion of these data are either not readily useable, since they are not always physically compatible and adequately quality controlled, or are not easily accessible. It is therefore essential that the resources of modern data processing and data retrieval techniques be applied to the management of climatological data and that an urgent effort be applied to developing internationally compatible formats, data processing and exchange procedures.

The primary responsibility for acquiring, storing, and retrieving climatological data should rest with national archives. It is urgent to organize a timely and direct flow of information between these archives. Consideration may also be given to regional archiving activities. With this in view it is recommended:

- (a) To prepare and maintain an Inventory of climatological stations;
- (b) To prepare and maintain a Catalogue of available reliable climatic data;
- (c) To collect, collate and make available a core of climatic data of a standard quality level and standard format from a representative global network;
- (d) To develop appropriate statistical processing schemes for condensing the mass of raw climatological data down to manageable data sets.

Once the presently available data have been identified, the next step is to pinpoint where the data gaps are on a national, regional, and global scale. To augment the data systems of many countries major support will be necessary to achieve the expansion of networks, data collection, quality control, processing and storage. It will be essential to provide an exchange of technology and to organize education and training to achieve viable systems.

6. CONCLUSIONS

6.1 Priorities

To improve the availability of reliable data for the purposes discussed at this Conference, it is proposed that participating nations, WMO, and other international bodies include the following tasks in their priority programmes, as appropriate:

- (a) To locate and assemble instrumental observations made during the last 100 years or more, examine the data for quality and consistency, and ensure that these data are readily available for both manual and computer processing (see Section 4.3);
- (b) To establish, maintain and improve the network of climatological stations (see Section 3.2.1);
- (c) To establish, maintain and improve the network of observations over the oceans (see Section 3.2.2);
- (d) To establish, maintain and improve networks of hydrological stations;
- (e) To establish a commonly agreed upon data management plan and promote data exchanges (see Section 5);
- (f) To collate, organize and process climatological data into readily useable formats (see Section 5);
- (g) To undertake a survey of sources of meteorological, hydrological, oceanographic, paleoclimatic, geophysical, ecological and socio-economic data, and establish a referral system on data sources (see Section 5);
- (h) To promote the development of new observing technology and, in particular, space technology applicable to climate monitoring on a global scale (see Sections 3.2 and 4.3).

Particular consideration must be given to developing countries by providing assistance for implementing the above priority tasks.

6.2 Goals of the climate data system

The success of applications, climate impact studies, and climate research depends upon the development of a vast and diverse data base including:

- (a) Meteorological, oceanographic, hydrological and geophysical data;
- (b) Biological and ecological data;
- (c) Sociological and economic data.

The primary goal of international co-operation on climate is the acquisition of the type (a) data referred to above that is necessary for documenting the present world climates and climatic evolutions.

A second goal is to stimulate the acquisition of the remaining elements of the data base (types (b) and (c) above), some of which are beyond the resources and competence of WMO, through the co-ordination of national and regional efforts with the appropriate specialized international bodies.

Highest priority should be given to the extension and improvement of existing climatological networks on the one hand, and on the other hand, the development of an internationally agreed upon compatible data system. With respect to the first point, particular attention must be given to increasing satellite data and to extending ground level observations, including those concerning the radiation and hydrological balance, and making worldwide oceanographic observations. With regard to the second point, highest attention should be given to developing compatible procedures and formats for timely collection, quality control, archiving, and exchange of climatological data in order to document the worldwide climate, to allow early assessments of significant deviations from the current global climate, and to ensure the availability of climate data to other users.

APPLICATIONS OF THE KNOWLEDGE OF CLIMATE

1. INTRODUCTION

During recent years, there has been a striking and rapidly growing realization by governments, as well as by the general public, of the dependence of national economies and human welfare on climate and its variability. This was particularly highlighted by recent important, although perhaps not abnormal, climate fluctuations in a world where nations have become increasingly economically and ecologically interdependent, but where until recently there existed a wide-spread belief that the main practical purpose of meteorology was weather forecasting.

To lessen this vulnerability to the vagaries of climate, climate knowledge has long been applied for the benefit of human welfare to both economic and environmental activities. In general, knowledge of climate and its characteristics is essential to support decision-making in two major aspects of human activities with different time frames: (a) planning and design and (b) operation and management.

Furthermore, the growing recognition of the important role to be played by the application of climatic knowledge in planning national socio-economic development has led to the realization of the need for more effective international action in this field. This need has been expressed by a number of major intergovernmental meetings organized by the United Nations, such as the Conference on the Environment (Stockholm, 1972), the World Food Conference (Rome, 1974), the Conference on Human Settlements (Vancouver, 1976), the Water Conference (Mar del Plata, 1977), and the Conference on Desertification (Nairobi, 1977).

2. THE USE OF CLIMATIC KNOWLEDGE

Climatological information can be applied to a wide variety of planning and operational activities in all nations. The most sensitive are those sectors dealing with food production, water resources, energy and human settlements and health. Socio-economic activities in those sectors have evolved over a long period of time and reflect adaptation to regional and local climates. In many developed countries, a reasonably adequate archive of climate data has been employed by climatologists to provide significant applied services to the relevant sectors. Unfortunately, however, planners and managers often underestimate climate as an economic variable and consequently make poor or little use of this socio-economic resource. Further, many developing countries need assistance to establish the necessary service organization and to train staff so that services in applied climatology might be provided to other government services and to the public.

2.1 Planning activities

When the general statistical characteristics of climate and its variability are known for a locality or a region, this information may be used to assist in the choice of a design or policy which is intended to remain in being for a long period of time. We may, for example, wish to design a water management system which will remain in operation for a century or more. Employing information on the mean precipitation and its variability, we would contribute towards the assurance that flood damage, availability of irrigation water, and costs were kept within bounds during that period with some degree of certainty. Other climatic knowledge could be applied to the planning of agricultural developments and to the introduction of new sources of energy (e.g., solar radiation, wind, tides, etc.). Such planning decisions are of great importance for economic development, particularly in the developing nations where major decisions involving climatic knowledge must be made within the next few decades.

Efforts to apply this climatic knowledge must be based on the statistics of climate and its variability.

2.2 Operational activities

Current climatic information can be of great value to managers of climate-sensitive operations on a day-to-day basis. For example, precipitation and snowmelt data are used in the operation of flood control systems and temperature and wind data are needed in managing fuel supplies in cold regions.

3. OBJECTIVES AND PRINCIPLES

3.1 Objectives of applications

The basic objective of a climate applications programme is to assist societies to improve their capabilities to carry out various activities, and to obtain maximum economic and social benefit under different climatic conditions while maintaining environmental integrity.

Specifically, international efforts relating to climate applications should seek:

- (a) To respond to the demands of users and determine the climate information needed for the most effective operation of climate-sensitive activities, or to reduce their vulnerability to climatic hazards;
- (b) To increase the awareness of planners and decision-makers of the uses of climatic information and to improve their capability to employ this information;
- (c) To devise, implement and improve operational programmes to provide this information and to assist developing countries in this task;

- (d) To assist both national services (meteorological and hydrological), particularly in developing countries, and managers of climate-sensitive activities in providing and using these services;
- (e) To disseminate information on climate applications, transfer relevant technology and facilitate training in climate applications;
- (f) To refine or state requirements for new climate and climate-related data and for research results needed for improved applications services.

At the international level, efforts should concentrate on the provision of climate information and methodologies to assist in dealing with regional or global problems. Such problems would include desertification control or preparedness for international disaster relief. Other efforts might involve the promotion of more effective management of agriculture and water resources than presently exist or the planning and development of new energy producing facilities. WMO and other international bodies are already involved, to varying degrees, in many of these actions; future planning should make full use of climatic applications in building on the present ongoing programmes.

3.2 Principles for development of an effective Applications Programme

Based on the experience of meteorologists, hydrologists and other experts in relevant fields, several general principles for the effective application of climatological information can be formulated. These have been clearly set forth by J.D. McQuigg in WMO TN No. 132, and may be summarized as follows:

- (a) In order to make effective use of climatological information, one must make active efforts: to identify climate-sensitive processes for which the needed information can be specifically defined; to develop documented, quantified relationships between climate information and activity; to produce the information in a usable form; and to communicate it to users who understand how to employ it in their decision processes;
- (b) Climatological information is likely to have the largest economic impact if it is produced and used before major resource use patterns are firmly established or before changes are made. If long-term strategic decisions are made without consideration of climatological information, it may be impossible to make optimum use of short-term weather information in the future management/operation of the system involved;
- (c) Specialized climatological information and guidance can usually be developed for a particular planning/design/policy decision for a small fraction of the total cost of the enterprise concerned.
- (d) Individuals who understand both the application and the nature of available climatological information play a crucial role in linking users and the information they need.

4. PROBLEMS AND DEFICIENCIES IN THE APPLICATION OF CLIMATIC INFORMATION

4.1 Availability and timeliness of the information

Climate information must be available and used before the decision is made, and before new patterns or procedures are being determined and established. Since climate information is based on multi-year records of past weather, unless the necessary networks have been in operation for years and the data collected and analysed, it will be impossible for climate factors to be taken into account in the decision process.

4.2 Trained personnel and tailoring information to the user's needs

A common requirement of all climate information users is for trained and motivated people. Skilled people are needed to translate user needs into clear requirements for climatological information and services, to develop specialized climatological products from generalized data archives, and to work with users in applying this knowledge to their problems, thereby increasing their awareness of the influence of climate on their activities, and hopefully improving the priority given to climatological services within the nations. Special needs for trained personnel in climatology can be perceived for such activities as: data processing, computer techniques, building and urban development, energy problems, air pollution, agriculture, water resources and offshore operations. These specially trained people will not all be employed by the meteorological services. However, the training must be at an advanced level because, amongst other activities, climatologists are frequently asked to evaluate environmental impact assessments and the experts called upon by the developers to prepare these assessments often resort to elaborate analyses that require a critical appraisal.

4.3 Transforming basic data into useful information

In some locations, adequate data exist upon which applications can be effectively based. However, in other locations data may not have been collected and organized into readily usable form (see Report on Climate Data). Even if basic data are conveniently available, these may need to be transformed into derived data products shaped to the needs of the various customer groups. For example, basic meteorological data may be converted in terms of parameters significant to the specific agricultural problems of a given location, e.g., length of growing season, probabilities of favourable or adverse conditions for planting, cultivation and harvest. This information must then be made available to planners and decision makers in a form convenient for their use.

One pervasive problem that arises here is the fact that climatic knowledge is often needed on the local scale, while basic data are usually available only on the macro-scale. For example, the location and design of a power plant depends on the local climate of the valley in which it is located, while the only climatological data may be available from an airport many kilometres away. Agroclimatic parameters may be needed for a small region, while the only data available may come from a conventional meteorological station with a different local climate or from a specialized

agrometeorological station with different environmental conditions. Thus, the provision of useful information from available data, however high in quality or quantity, is neither straightforward nor simple.

4.4 Resources for climatic applications

The growth and strengthening of meteorological services in developing countries, and the allocation of resources for this purpose has tended to give priority to the establishment of synoptic networks, the provision of operational services to aviation and other real-time weather observing and forecasting activities. In contrast, the less visible, less glamorous, but also less expensive development of networks of climatological stations and climatological services appropriate to the development of the resources of the country has received lower priority and few resources and in fact has often been carried out by other than the meteorological service. This has presumably resulted from the unawareness of development planners and managers of the potential value of climate knowledge available to them, and also because the more immediate effects of the weather, that may endanger life and property, are more likely to attract the attention of the responsible authorities in government. Another major obstacle to the applications of climate knowledge is the frequent inadequacy or absence of systems for data archiving and retrieval - an obstacle which occurs in some developed as well as developing countries. Satellite observing systems present special problems in this regard.

In some instances, resources for climatological services to users may be provided from outside the country through bi- or multi-lateral aid programmes. But the primary source of support for any nation's basic services must, in the long run, be its own resources. In all cases, climatological applications programmes should be given support that is proportional to their potential contribution to socio-economic development and human welfare.

4.5 Dissemination of information

Climate information potentially relevant to the solution of national problems increases rapidly, while the finite national resources of manpower, expertise and funds to acquire this information grow but slowly. Furthermore, in a developing country there may be only a handful of experienced climatologists and insufficient funds to acquire the world's technical literature. Yet the country may face in a single generation the full range of problems already experienced by a major industrialized nation over several centuries. Special efforts are therefore needed to ease and accelerate the flow of information.

In addition to basic and specialized climatic data the requisite information includes derived data products, atlases, annotated bibliographies pertaining to climate applications, specialized technical reports, computer software, and guidelines for the development of such information dissemination vehicles as publications, seminars, demonstrations, etc.

5. AREAS FOR INTERNATIONAL ACTION

Climate applications services should be commensurate with the needs and consistent with feasibility in different nations and geographical areas. Although considerable services already exist international actions are recommended to satisfy further major needs. These include:

- (a) The promotion of the use of applications (e.g., by more effective interaction with users, education, the use of interdisciplinary studies of economic benefits, etc.);
- (b) The development of an appropriate data information system (e.g., by the integration of data from different sources, the creation of archives that are more complete and of improved quality);
- (c) The more effective and efficient development of new methodology (e.g., by developing more efficient means of extracting desired information from basic data);
- (d) More effective technology transfer, particularly to developing countries (e.g., by expanding and systematizing present activities, increasing assistance, improving computing facilities, providing more manuals in user's language, etc.);
- (e) Development and implementation of related educational and training programmes (e.g., by expanding and systematizing training conferences, seminars, pilot programmes, and increasing and improving training and material assistance).

These areas for potential action, which are not presented in an order of priority, are described in the following sections.

5.1 Promotion of the use of climate applications

Although recent climatic events have increased the awareness of users and potential users of the value of climatological information, obstacles remain to optimizing its use. Users may not grasp the full potential value of applying climatology to their problems; climatologists often lack an understanding of the decision processes of and alternatives available to potential users; in other cases, organizational circumstances act to reduce the effectiveness of a climatological applications service. Although these problems are common throughout the world, the necessary remedial measures may vary with levels of development and the socio-political system. While strategies for promotion may differ from one country or region to another, within all countries the interface between climatologist and users must be further developed so as to remove perceptual barriers. Consumer involvement can be greatly enhanced by the use of committees, where the user is free to express his views, and by improved understanding of his activities by applications climatologists. Because of the existing resource limitations the scope of the applications programme ought to be directed toward high priority activity sectors where early benefits will be considerable, e.g., agriculture, water resources, and energy.

In many developing countries, there is a need for internal recognition of the importance of climatological services. Observational and applications programmes may be undertaken by a variety of agencies and consideration should be given to their consolidation within, or co-ordination through, a central climatological service, thereby providing a more appropriate data base and decreasing considerably the cost of the total system necessary for an effective applications programme.

While many of the problems are national, international efforts could help stimulate the intelligent applications of climatology by such actions as the following: (a) documenting and publicizing selected pilot projects in climatological applications; (b) conducting selected case studies demonstrating the efficacy of specific climatic services since few countries have identified in a convincing manner the major benefits that accrue through the applications of climatology; (c) organizing visible activities such as seminars, symposia and conferences dealing with the methods and benefits of climatic applications and involving users, climatologists and political leaders. Very effective interaction techniques have been identified by WMO and recorded in the report of the WMO Solar Energy Meeting, October 1978. These involve meetings at all levels of programme development including technical conferences, seminars and workshops at the regional level where the participants are few, but well selected. The use of "roving" seminars should be encouraged because they reinforce local interest and training relevance.

5.2 Development of a data information system

A climatologist cannot effectively serve a client if he does not have access to a reasonably adequate climatic data base. Such a data base must usually cover a period of at least 10 years, and the longer the period of record the better will be the climatological statistics that can be derived from it. While it is recognized that provision of services related to data is largely a national matter, certain efforts might be undertaken internationally, for example:

- (a) Development and dissemination of regional climatic atlases and other data products relevant to such applications areas as land-use planning, pollution control, etc.;
- (b) Preparation and distribution of bibliographies and specialized technical reports;
- (c) Operation of an international bibliographic research service which could readily assemble the most relevant world literature bearing upon a problem presented by a national application specialist;

(for further information see the Report on Climate Data).

5.3 Development of new methodology

At present, new applications methodology is largely being developed on an ad hoc limited national "needs" basis. This leads to redundancy and the development of products that do not necessarily make use of the best methodology. Continued

development of applications methodology on an efficient, best-use-of-science basis is essential in the interests of both developing and developed countries. Co-ordination and integration of this effort is essential.

Multidisciplinary studies of the interaction between climate and human activities should be stimulated because these are a potentially useful tool for developing programme priorities and strategies.

Operational climatological services that combine knowledge of current hazard or opportunity levels determined from recent climatic and other information together with the information content of current weather forecasts can provide major benefits to a community or sector of industry. Such services are invaluable in periods of impending drought, or when combined with user information for operations such as fertilizer application and soil conservation. The development of this type of service should be encouraged and supported as a matter of priority.

Also, the possibilities for an international "climate alert" system deserves exploration.

5.4 Technology transfer

Much experience and technology relevant to the application of climate knowledge to human problems already exists. However, many potential applications have not yet been adequately developed, while applications developed in one country may not be immediately transferable to another. The technology transfer process requires: knowledge of what is required, what is available and what is transferable to the areas of need; the development or modification of applications to suit requirements; the development of the support systems and of the education, training, and other actions needed for implementation. Technology transfer may be relatively simple as in the case of satellite photo interpretation, or complex where the development of major new physical plants and expertise is involved.

A significant effort in climate-related technology development should focus upon the needs of the developing countries. Considerable effort, for example, has been devoted to research on climatic effects on wheat, but little work has been done on, for example, tef or cassava, although these crops play a major role in the economies of numerous countries. Efforts are needed to increase research and development in climate-related problems, especially those of developing countries.

The following priorities are identified in the technology transfer area:

- (a) Inventories of internal needs and both internal and external capabilities;
- (b) Information regarding the availability of technical assistance;
- (c) Local experts to work with and advise external technical experts;
- (d) Computing facilities at centralized locations;

- (e) Information and computer software packages to transform climatic data into user-relevant parameters;
- (f) Adaptable numerical models for such applications as pollution assessment, crop-weather evaluation, agricultural zoning, water-resource assessment, etc.;
- (g) Continued and strengthened technical publishing programmes;
- (h) The provision of relevant guides, manuals and technical journals and other such reference material from other countries;
- (i) Co-ordination and interaction of relevant national and international agencies.

The transfer process requires the use of regional training seminars and demonstration projects which are the subject of the next section of the report.

5.5 Education and training

People are usually the critical elements in the application of climatological information. There are needs for:

- (a) Broadly qualified climatologists knowledgeable in applications areas who can interpret user needs in climatological terms and assist users in employing climatic information in their planning and decision processes;
- (b) Specialists from other disciplines, such as agriculture, hydrology or marine activities with an appreciable knowledge of climatology;
- (c) Data specialists who can transform existing archives of general-purpose data into special-purpose information for specific applications;
- (d) Technicians to apply computer and other modern technologies to these tasks.

While experts from outside may from time to time assist in providing these needs, in the long term these people must come from a nation's own resources. Indeed, training within a country is most likely to develop expertise in that country's unique problems and relate more closely to national priorities.

International efforts can assist by:

- (a) Providing guidelines for educational requirements, syllabi, and qualification standards for climatological experts;
- (b) Developing reference and instructional material for use in climatological training;

- (c) Co-ordinating fellowships, exchange and similar programmes to provide educational/training opportunities for developing-country personnel in countries with climatological expertise;
- (d) Co-ordinating assistance programmes for in-country educational programmes, including arranging for instruction, course materials, etc.;
- (e) Helping develop suitable climate applications training centres, especially in developing countries, e.g., at universities, institutes and technical schools.

In some developing areas regional centres may be useful, especially for the training of specialists who will become instructors. Regional training programmes are often a very efficient way of stimulating the implementation of applications programmes within developing countries. Regional training seminars of a roving nature have been particularly effective, for example, in the area of hydrological applications. Such types of activity should be expanded on a "needs basis".

The Voluntary Assistance Programme (VAP) of WMO has been adopted as a means for providing technical assistance, equipment and training for developing countries. Hitherto the VAP has been restricted to support of the WWW Programme. It is urged that the VAP be extended to provide appropriate assistance in applications of knowledge of climate and the use of climatic data. Other United Nations bodies have similar programmes and these too should be used in support of the applications programme.

6. PRIORITIES

6.1 Priorities of socio-economic sectors

The climatic problems related to the activities listed below are becoming increasingly significant and they should therefore be considered as a matter of urgency in combination with the five areas indicated in Section 6.2 of this report.

The applications of climatology to the following specific areas should receive high priority generally, but relative priorities will depend on local situations:

- (a) Food production - agriculture, fisheries, alleviation of crop and animal disease, soil conservation, land-use, desertification control;
- (b) Water resources;
- (c) Energy - exploration, production, transportation, conservation, demand;
- (d) Human health and settlements - building and construction, tourism and recreation, environmental pollution control, natural hazards;

- (e) Transportation and communications, manufacturing and other industry;
- (f) Marine and coastal zone development.

6.2 Priorities of areas for international action

The major areas (see Section 5) have been presented in a manner that does not reflect their priority. Priorities differ from one geographical region or nation to another, and among other things they are dependent on feasibility. Nevertheless, it is possible to assign overall priorities, as follows, recognizing that they may not have universal application:

- (a) Development of an appropriate data information system;
- (b) Development and implementation of applications education and training programmes;
- (c) More effective technology transfer;
- (d) The promotion of the use of applications;
- (e) The more effective and efficient development of new technology.

7. ORGANIZATIONAL QUESTIONS

The application of climatic knowledge relies on the interaction of experts with knowledge of climate and users in a wide variety of application areas. Within individual countries, we have seen that close co-operation between climatologists and users is essential for success. Similarly we should expect that co-operation between WMO and other specialized international organizations would be desirable in the planning and implementation of an international applications programme.

In this light, the following ideas should be considered:

- (a) At the national levels: National committees to co-ordinate and stimulate the application of climatic knowledge would be useful. Such a committee might include representatives both of the government services having climatic expertise and of operational and planning sectors of the national economy, such as agriculture, water resources, energy, marine resources, etc.;
- (b) Within the WMO: There are many ongoing programmes and projects within WMO that relate directly or indirectly to applications. Technical Commissions and Regional Associations are involved in many appropriate aspects of applications of climatology to various fields of human activities. Co-ordination steps should be taken as needed to improve existing capabilities and encourage useful new efforts.

- (c) Among international bodies: It is necessary to improve the co-ordination of efforts by climatologists and users at the international level and, at the same time, to facilitate the co-ordination between specific international bodies and corresponding national authorities. Among the terms of reference of international groups or committees would be: definition, planning and evaluation of co-operative international projects as appropriate; assistance to national and international programme planners in drawing upon the resources of co-operating international agencies; and co-ordination by commitments of national resources to international programmes.

8. GOALS OF THE CLIMATE APPLICATIONS PROGRAMME

In many parts of the world, there is sufficient information to provide applied climate services. These are invaluable for planning social and economic development and for day-to-day management decisions. Through the application of climate information, planners and operators can reduce the vulnerability of society to climatic extremes. However, only a start has been made; data and expertise are generally lacking in developing countries while, everywhere, effective methodologies for use in climate-related problems need yet to be developed.

Although a wide variety of planning and operational activities are sensitive to climate, the most sensitive are food production, water resources, energy and the very important sector of human settlements and health. In serving each of these applications, climatologists must work with agriculturalists, engineers, etc., as well as with others within national weather services - data specialists, researchers, etc. Only co-operative efforts can make the goals of the WCP attainable.

Specific goals of the climate applications programme must be to enlighten people and policy-makers of the value of applying climate knowledge to socio-economic problems and to ensure that this knowledge is available. Action plans therefore must include programmes to assist national meteorological and hydrological services to (a) increase the awareness of users of the potential benefits to be gained through the use of climate information; (b) improve capabilities to provide and disseminate this information and (c) facilitate training in nationally significant climate applications. Other action plans, on a global scale, must include programmes to develop new methodologies for the application of climate data in the food, water, energy and health sectors. Finally, there must be programmes set up to assist developing countries to participate fully in the WCP through training and the transfer of appropriate methodologies.

THE INFLUENCE OF SOCIETY ON CLIMATE CHANGE AND VARIABILITY

1. INTRODUCTION

Since the birth of civilization, mankind has experienced changes of climate, but no large scale man-induced change has ever been documented. However, with a large and increasing world population and with human activities on an increasing scale, man now appears capable of inadvertently altering the climate of this planet within the next few generations to an extent comparable with major natural climatic changes. There may now be the opportunity for man to use knowledge and wise action to avert the adverse effects of such changes.

The present state of our scientific understanding of climate does not permit confident predictions as to the nature of the changes likely to result from human activities nor as to the rate at which such changes would occur. However, that understanding is sufficient for it to be suggested that certain human activities, if maintained at their current levels or pursued on an increasing scale, could lead in the decades ahead to changes in climate which would have profound effects upon mankind. There is therefore a special sense of urgency for the establishment of an international research programme to examine the various aspects of human impacts upon climate, giving special attention to the accumulation of carbon dioxide in the atmosphere, a subject which merits immediate attention.

2. HUMAN INFLUENCES ON CLIMATE

Human influences on climate cannot be considered in isolation, but need to be examined in the context of the natural variation and evolution of climate in the future, with all its subtle ramifications with regard to our overall human environment and to social and economic development. A great deal of research is required so as to be able to discriminate between climatic variability and changes that occur naturally and that are the result of human activities. Present estimates suggest that our climatic destiny will probably continue to be dictated mainly by natural geophysical processes at least until the end of the present century. Thereafter, however, man himself may well hold the key as to developments in the global climate, mainly from the beginning of the next century, and to that extent may largely influence our longer-range fate with regard to climate.

The World Climate Conference has focused part of its attention on those activities of man which may influence the climate of the earth. These influences are seen to include the emission of carbon dioxide and other infrared absorbing gases to the atmosphere, changes in the nature of the land surface, military activities, increased concentration of aerosols, effects on the ozone layer, discharge of waste heat, and weather and climate modification.

Since no nation alone could deal with such issues, planning for climate change or action to avert the adverse effects of such events must clearly take place internationally. As an example, if fossil fuel use is to be curtailed, worldwide action must be taken to be effective. Such decisions will have to be implemented with the recognition that some nations and regions will benefit while there may be considerable cost to others.

3. CATEGORIES OF MAJOR HUMAN IMPACTS ON CLIMATE

Man's activities of various kinds may contribute to changes of climate. The principal climatic effects of these activities, however, are likely to differ as to both the geographical scale of the effects and the period of time over which the effects may accumulate. Clarification of the temporal and spacial scales of these climate modifying processes is urgently required.

The more important categories of human impacts on climate may be identified and are briefly described in the following sections.

3.1 Carbon dioxide release from fossil fuel combustion and deforestation

The release of carbon dioxide (CO₂) to the atmosphere by man, involving carbon that had been withdrawn from the atmosphere through photosynthesis or otherwise a relatively long time ago, is capable of resulting in an accumulation of CO₂ in the atmosphere. Such an accumulation has been reliably observed to occur in measurements of background CO₂ levels since the International Geophysical Year in 1958 (amounting to about 5 per cent in that interval). The climatic effects of CO₂ occur through its absorption of infrared (heat) radiation which results in a global warming of the lower atmosphere; this is commonly referred to as the "greenhouse effect". The rise of atmospheric CO₂ concentration in this century has not yet been sufficient to produce measurable warming of the lower atmosphere. However, current projected trends in CO₂ concentration may lead to significant warming early in the next century. Indirect climatic effects on atmospheric circulation and precipitation and evaporation (hydrological cycle) are also likely.

There are many interacting mechanisms which determine climate and account for the complexity of the problem of predicting the influence of carbon dioxide and other infrared absorbing gases. The stability of polar ice sheets is a matter of concern. Model experiments suggest that the polar regions will probably experience greater warming than the equatorial regions, an effect that would lead to changes in the large-scale circulation of the atmosphere and ocean, with concomitant changes in precipitation and temperature patterns over most regions of the globe. A marked warming of the polar regions would clearly influence the distribution of ice and snow, giving a possibility of the Arctic ice pack disappearing, at least in the summer months. Such a warming would also give rise to concern about the polar ice sheets, especially the West Antarctic ice sheet which, being grounded below the sea level, may be more liable to wastage and thus contribute to a world wide raising of the sea level.

3.2 Other infrared absorbing gases

Several other gases, also released to the atmosphere as a consequence of human activities, are similar to CO₂ in their radiative effects and therefore in their potential impacts on climate. Among these gases are chlorofluoromethanes (used for refrigeration agents, spray-can propellants, and other purposes), carbon tetrachloride and methylchloroform (used as industrial solvents), and other chlorine compounds that evidently possess very long residence times in the atmosphere and that are observed to be accumulating. Nitrous oxide is also to be identified in the same category of long-range concern, in view of the possibility of massive additions to the atmosphere over the next century through the decomposition of nitrogen compounds stemming from industrial, domestic and agricultural activities. Not enough is known about the behaviour of these and other gases, and it is possible that some processes involving them could lead to a cooling of the atmosphere.

3.3 Changes of land surface

In the course of time the surfaces of the continents are increasingly being altered through various activities of man. In many areas forests are being cleared for agriculture, massive water impoundments and irrigation systems are being constructed, roads are being built, and urban areas are being expanded. Every such alteration of the land surface has the potential to influence climate on a local or regional scale. This influence arises through one or more of four main effects:

- (a) Changes of surface roughness, which governs the exchange of momentum and energy of air motion between the atmosphere and the ground;
- (b) Changes of surface albedo, which governs the fraction of solar radiation converted to surface heating;
- (c) Changes in thermal characteristics of the ground and in heat transfer to the atmosphere; and
- (d) Changes of moisture holding capacity of the surface, which cause the flow of water between the surface and the atmosphere to be redistributed in space and time.

Such influences on climate can be significant on a local level. Their importance on larger scales, however, is less clear, and this remains to be clarified through appropriate studies of regional or global scale climate.

3.4 Stratospheric changes

Changes of ozone and other chemical constituents of the upper atmosphere may arise through the introduction of certain pollutants from man's activities. These changes depend on complex chains of chemical reactions capable of being altered by chlorine compounds (e.g., chlorofluoromethanes) and other materials introduced into the stratosphere by human activities. It has been estimated that the continued worldwide production of chlorofluoromethanes in the quantities produced in the decade of the 1970s might cause a gradual depletion of total atmospheric ozone accumulating to

about 15 per cent by the middle of the next century. An ozone loss, in turn, would weaken the ultra-violet screen which may significantly affect the biosphere and human health. The effects on climate of a depletion of stratospheric ozone may be significant, but this again requires verification through climate modelling experiments in which stratospheric chemical processes and effects are adequately represented.

3.5 Atmospheric particles (aerosols)

Many human activities produce particulate materials (dust, smoke, etc.), or gases such as sulphur dioxide that are later converted to particles by hydrolization in the atmosphere. As a result of air pollution control measures in many nations, releases to the atmosphere of large particles have decreased in recent decades. Particles smaller than one micrometer, however, are still produced (or later develop from sulphur dioxide releases), and it is these small particles that may have important effects on the passage of radiation through the atmosphere. The net effects of future changes in the populations of such particles on climate are now estimated to be quite small, except locally or regionally in areas of very high particle concentrations (i.e., urban or industrial areas, or certain agricultural regions of the world). The net influence of atmospheric particles on temperature or precipitation is difficult to assess without detailed information concerning the particles and the chemical and photo-chemical processes involved, and may be in the direction of either cooling or warming, and either greater or less cloudiness or precipitation. Such climatic effects are difficult to assess but, based on present information, appear to be small.

3.6 Heat emissions

As the end product of virtually all energy used by man, heat is released in substantial quantities either directly or indirectly to the atmosphere. Much of this heat is released from electric power stations and from heavy industry. The total of all heat releases to the atmosphere by man is now, and will continue to be for a considerable time to come, very small compared to the flow of solar radiation to the earth. However, heat releases are not now, and will not be, distributed evenly over the surface of the earth. It is the concentration of heat emissions that have local effects and could have impacts on the regional scale. Large-scale impacts on climate are not expected to arise from this source in the foreseeable future.

3.7 Weather modification

In certain areas of the world efforts are made to modify the local weather for particular purposes, e.g., to induce rainfall or to suppress hail formation. If these activities were to develop more widely, it might become necessary to examine the possible effects on climate on a regional and perhaps larger scale.

3.8 The military aspect

Among the human activities which have an impact on the world's climate it is necessary to include the possibility of military conflict. Global thermonuclear war, besides its catastrophic consequences for mankind, would degrade the natural environment and might cause climatic changes on a large scale.

4. CONCLUSIONS

Of the several forms of potential human impacts on climate already identified, the impacts that may arise specifically from the accumulation of carbon dioxide in the atmosphere deserve most urgent attention of the world community of nations. This is warranted because:

- (a) Long-continued reliance of society on fossil fuels as a principal energy source in the future, along with continued deforestation, is seen as likely to result in massive atmospheric CO₂ increases in future decades and centuries;
- (b) Our present understanding of climate processes leads us to recognize the clear possibility that these increases in CO₂ may result in significant and possibly major long-term changes of global-scale climate;
- (c) Carbon dioxide added to the atmosphere by man's activities would be removed slowly by natural processes, and therefore the climatic consequences of increased CO₂ concentrations would last for a long time.

Similar concerns to those expressed above also arise with regard to potential increases in other trace gases which have a greenhouse effect and which have very long residence times in the atmosphere, but which in many cases would have less profound economic consequences should it be desirable to reduce their emissions to the atmosphere in the near future.

Research should be accelerated at the national and international levels on various aspects of the CO₂ problems in order to determine the effects of increasing CO₂ on global and regional climates, on the carbon cycle within the atmosphere-ocean-biosphere system, and the socio-economic consequences of these effects.

IMPACTS OF CLIMATE CHANGE AND VARIABILITY ON SOCIETY

1. INTRODUCTION

Many examples of the interaction between climate and human activities were described in the overview papers and in the discussions during the first week of the World Climate Conference. The impacts of climate on society were presented according to sector (energy, water resources, health, forestry, fisheries, marine resources and offshore development) and for agriculture in various regions (temperate zone, humid tropics, semi-arid tropics; China, Latin America, Africa). In addition, an attempt at an integrated analysis of the macro-economic consequences of climate changes was presented. The presentations and discussions suggested that climate may be considered both as an asset to be wisely used and as a problem to be overcome.

In a rational allocation of resources between work relating to climate and other efforts towards improving the well-being of society, reliable estimates of the socio-economic impacts of climate changes and variability are of primary importance. A proper analysis must establish both the magnitude and distribution of the benefits and the costs of climatic impact. Such an analysis is not an easy task. While some impacts are direct and obvious, others are less so; secondary or indirect impacts may sometimes produce larger effects than primary ones. A full assessment of climatic impact must trace its consequences well into the economic and social fabric of society and examine the whole complexity of linkages and feedbacks in climatic impacts on the biosphere and on human activities. In this connexion, analyses of sensitivity of climate-society interactions are among the most important tasks to be undertaken.

2. CLIMATE CHANGE AND VARIABILITY

Fluctuations and variability have always been characteristics of climate and weather. The perception of the impact of these characteristics has intensified over the last decade. This has given rise to an increased anxiety in relation to potentially adverse consequences should significant climatic changes occur (such as a steady drop in temperature or a possible marked warming, more frequent droughts and desertification, or even changes in the sea level).

Unfortunately, there is little agreement among scientists on the magnitude or timing of possible future climatic change. Much scientific work remains to be done on the collection of climatic data, the determination of future climatic changes and the forecasting of their consequences. The importance of possible trends, possible

cyclical behaviour and other variations of climatic elements with time needs further investigation and research. Scientists and governments of all countries should be responsible, where necessary with international help, for an increased effort in scientific research, in informing their populations and in training specialists. Furthermore, governments will need to consider capital outlays so that the above objectives may be met and measures taken to prevent or lessen possible unfavourable consequences arising from fluctuations or changes in climate.

3. THE INTERACTION OF CLIMATE AND SOCIETY

The character of the impact of climate in a given region will depend in part on the nature of the climatic fluctuation and in part on the nature of the society. Thus, for example, the occurrence of extremes may have a sudden effect (as in floods or frosts) or a gradual effect (as in droughts or permafrost). Impacts of climate fluctuations may be manifested in different ways depending on the environmental and socio-economic conditions in the countries or regions concerned. Interactions between climatic fluctuations, environmental conditions, socio-economic status and other infrastructural factors can cause significant differences in the vulnerability of different regions to given climatic variations.

Climatic impacts affect many aspects of human activity. These include (1) human health and capacity to work; (2) housing and settlements; (3) agriculture of all types; (4) development and management of water resources; (5) forestry resources; (6) fisheries and marine resources; (7) energy production and consumption; (8) industry and commercial activities; (9) transportation and communication; (10) public services of many kinds. All of these provide possible areas for an investigation of the interaction between human society and climatic variations.

Certain regions and states - for example the economically less-developed regions, regions affected by armed conflicts, states with a large number of illiterate and poor members of the population, states with limited resources, states technically underdeveloped without their own specialists and unprepared for combatting the distress caused by the elements - can be specially susceptible to climatic variability resulting in conditions of economic disaster and severe suffering, especially amongst the impoverished sector of the population. However, this increased vulnerability is a complex combination of climatic and other factors.

While societies will experience climatic impacts in a range of ways, two essential categories of impacts may be identified:

- The impacts of variable climate on basically stable or resilient sets of socio-economic factors with other elements of the environment held constant; and
- The impact of specific climatic perturbations on social and economic sub-systems which may be changed irreversibly while attempting to adjust to the impact.

While it is possible to determine objectively the nature of climatic variations on the basis of climatic statistics, the vulnerability of a society will depend on its own ability to respond under stress. This ability varies from country to country, and from one time to another, and it will be possible to express many points of view about it.

4. OBJECTIVES FOR AN IMPACT STUDY PROGRAMME

The ultimate objective of an Impact Study Programme within the World Climate Programme should be to bring to light the importance of climatic considerations in the formulation of rational policy alternatives. In areas of the world characterized by different natural environmental conditions, social structures or economic systems, and differing levels of development, there can be different interactions and responses to climatic variability. The basic studies should aim at an integration of climatic, ecological and socio-economic factors entering into complex problems of vital importance for society such as availability of water, food, health conditions, energy resources, etc. The following objectives should be given special attention:

- (a) Improvement of our knowledge of the impact of climatic variability and change in terms of the specific primary responses of natural and human systems (such as agriculture, water resources, energy, ocean resources and fisheries, transportation, human health, land use, ecology and environment, etc.);
- (b) Development of our knowledge and awareness of the interactive relations between climatic variability and change and human socio-economic activities;
- (c) The improvement of the methodology employed (e.g., case studies and models) so as to deepen the understanding and improve the simulation of the interactions among climatic, environmental and socio-economic factors;
- (d) Determining the characteristics of human societies at different levels of development and in different natural environments which make them either specially vulnerable or specially resilient to climatic variability and change and which also permit them to take advantage of the opportunities posed by such changes.

5. METHODS IN AN IMPACT STUDY PROGRAMME

The approaches and methods to be used in climatic impact analyses must be selected with a view to effectiveness, time and resource constraints, consistency, compatibility, comparability and credibility of results. They must also allow for periodic review and evaluation and take full recognition of the many disciplines that must be involved if the programme objectives are to be met.

Historical case studies have a special place in climate impact studies in their own right. Lessons from the past can be used directly by decision-makers where a close analogy exists between a past situation and the present. Furthermore, just as empirical relationships are often incorporated in physical models of the atmosphere and oceans, so do case studies of the interactions of society provide parameterizations that can be used in socio-economic models by testing them against past situations, provided the information is sufficiently detailed.

When relationships are more obscure, involving many factors in complex feedback or non-linear interactions, relatively complex models will be needed that integrate socio-economic factors with directly impacted activities. Such models will be useful both in research to develop improved understanding and in practice to evaluate with more confidence the relative merits of different technologies, infrastructures, land-use, energy policies, etc.

The interdisciplinary character of the problems underlines the usefulness of mathematical models. In particular, existing models (such as models for food production and sectoral or national economic models) should be adapted to allow the inclusion of climate variables among the inputs.

In summary a wide range of approaches (historical case studies and examples, simpler analogue and extrapolation models, relatively complex integrated models with feedback) will be needed in any Impact Study Programme. The historical analyses will provide highly credible appreciations of potential risks and consequences. The simpler, specialized models can be used for testing alternatives. The complex models, which will still have to be developed in greater detail, will provide a multidisciplinary approach and should be the result of work by interdisciplinary teams of scientists and experts with a full knowledge of practical problems in order to identify areas of sensitivity for changes of climate of different types and magnitudes.

6. TYPES OF STUDIES

A large number of potential candidate study areas were proposed in the overview papers presented to the WCC and in the discussions during the conference. In considering the types of studies to be undertaken, it should be noted that the proposals in the draft Plan of Action recognized studies on a global scale as well as in specific geographical areas, and studies by socio-economic sectors (agriculture, water resources, energy, ocean resources, etc.). The validity of such a division was fully recognized. Nevertheless, another typology of studies has also been identified. Thus the types of possible studies could be grouped as follows.

6.1 Review and synthesis of existing knowledge

One example of such a study would be a summary of existing knowledge of interactions between climate and society based on historical information and case studies. Another might be a survey of existing quantitative models (sectoral, or national econometric models, or global system models) which take into account climatic variables.

6.2 Geographic, sectoral and societal studies

There is an urgent need for preliminary impact assessment in terms of risks and benefits of alternative courses of action, particularly in areas where climate may have major effects on human welfare. Under this heading would be included case studies and models which incorporate climatic inputs relating to agricultural activities in a number of critical regions (e.g., semi-arid areas or the humid tropics). The complex interactions between climate and water resources and between climate and energy would also come under this heading.

6.3 Studies urgently needed for developing countries

An example here is the effect of climate and climate change on human health and disease. A second example would be studies on disasters (such as floods, droughts and desertification) which have a particularly severe impact on developing countries. Of great importance for developing countries would be research on the vulnerability and resilience of various types of societies to climatic variation and change. ~~The Sahel region in Africa could serve as a case study in this type of research.~~

6.4 Methodological studies

One example under this heading would be the use of the results of climate model experiments to study the possible ranges of impact of the regional changes in temperature and precipitation that may occur with increasing carbon dioxide. A second area of study might be research on the inclusion of climatic inputs in sectoral, national and global econometric models. A third example is the study of the anticipated response of governments and peoples to new information regarding climatic variability and change.

It will be noted that the above identification of types of studies and the illustrative examples quoted are in agreement with the view of the WMO Executive Committee as expressed in the annex to Resolution 19 (EC-XXX), Part B.

7. CRITERIA FOR PRIORITIES IN AN IMPACT STUDY PROGRAMME

An important part of any plan of action is a set of criteria to be used in the identification and selection of problem areas which should be investigated. An initial programme should concentrate on problem areas which have more than one of the following characteristics:

- (a) Capable of serving the urgent interests of developing countries or a common need of all countries;
- (b) Concerned with problems of sectoral or regional importance;
- (c) Related to theoretically significant and scientifically important problems (e.g., analysis of global systems or the CO₂ problem);
- (d) Multidisciplinary and interdisciplinary (including the social and economic sciences).

The criteria suggested above relate to the intrinsic characteristics of each potential candidate project. They may be used to arrive at a preliminary selection. In order to arrive at a final selection of projects with a certain order of priorities, it would be necessary to take into account additional considerations, such as the following:

- (a) High priority should be considered for the studies which may be developed in association with other existing programmes so as to maximize utilization of resources. There are a number of examples of climate-related programmes carried out by other international organizations: FAO agricultural programmes; programmes of the consultative group for International Agricultural Research; Unesco programmes such as MAB and IHP; UNRISD programme on food systems; UNEP programme on desertification; ICSU programmes (e.g., SCOPE projects on biogeochemical cycles, etc.).
- (b) Some studies may be carried out by individual countries or groups of countries, either independently or with varying degrees of support from international sources. The international Impact Studies Programme should complement, not duplicate, these programmes.
- (c) Selection of case studies should be made with a knowledge of the content of other internationally or nationally sponsored studies, so as to achieve a wide spectrum of cases of interest from the point of view of the objectives of the overall Programme.
- (d) Efforts should be made to ensure that the environment in the institutions in which the projects will be carried out is favourable to interdisciplinary research, which is a necessary condition for progress in such a complex field of investigation.
- (e) Before a final selection of projects is made, there should be a feasibility study of the availability of data, research workers, resources, etc., in order to ensure that each project will give the maximum possible return for the investment in it.

8. DRAFTING AND IMPLEMENTING AN IMPACT STUDY PROGRAMME

The thirtieth session of the WMO Executive Committee invited the Secretary-General, in consultation with the Chairman of the WCC Organizing Committee and other experts, to establish a small working group to "formulate a draft plan on climate impact studies for consideration and adoption by the WCC". It was considered by the working group that Part 4 ("Programme of action to study impacts of climate"), of the document entitled "Action Plan for Programme of Studies on the Impact of Climate on Mankind" submitted to the World Climate Conference by the Conference Chairman included useful guidance for the elaboration of an action plan on the impacts of climate on mankind. It was also noted by the working group that the above document served as a basis for the proposals on the Impact Study Programme included in the document "Proposed Plan for the World Climate Programme 1980-1983" by the Secretary-

General (Part III of Appendix C to Cg-VIII/Doc. 44). It is recommended that a more detailed plan of action and a scientific programme should be prepared by a group of experts of a multidisciplinary character, in co-operation with interested international governmental and non-governmental organizations, guided by the above-mentioned documents as well as by the considerations set forth in this report.

While the criteria for the selection of projects outlined above are valid for at least one decade and thus the general plan of action would be valid for at least a similar period, it is more realistic that for the period 1980-1983 only a small number of projects (less than a dozen) be undertaken. The final selection of projects can only be made by the responsible planning groups after approval of the general plan of action. The identification of potential candidate projects and the planning and selection of these should be done by interdisciplinary groups, which should take into account the criteria mentioned. On the basis of the detailed plan of action, funding of urgent selected projects should be sought from all appropriate national and international sources.

The working group noted with appreciation that, in organizing the World Climate Conference, WMO has moved effectively to involve researchers from the many disciplines required for the assessment of the interaction between climate and society. The accomplishment of the latter task will not be easy. The working group therefore hopes that all interested international governmental and non-governmental organizations will co-operate in the follow-up to the Conference and in the implementation of the Plan of Action.

RESEARCH ON CLIMATIC CHANGE AND VARIABILITY

1. NATURE OF THE PROBLEM

1.1 Objectives

Our social and economic life is vulnerable to periods of climate stress. Human activity may itself influence local, regional and global climate. These are problems which the international community should address through a World Climate Research Programme (WCRP) which will attempt to determine why, how and where climate changes and variations occur, and thereby attempt prediction of their future occurrence.

The major objectives of a World Climate Research Programme should be to determine:

- To what extent climate can be predicted;
- The extent of man's influence on climate.

To achieve these objectives it is required:

- (a) To improve our knowledge of global and regional climates, their temporal variations, and our understanding of the responsible mechanisms;
- (b) To assess the evidence for significant trends in global and regional climates;
- (c) To develop and improve physical-mathematical models capable of simulating, and assessing the predictability of, the climate system over a range of space and time scales;
- (d) To investigate the sensitivity of climate to possible natural and man-made stimuli and to estimate the changes in climate likely to result from specific disturbing influences.

1.2 Climate defined

There have been a great variety of definitions distinguishing climate from weather. For the purposes of this document we adopt the following:

- Weather is associated with the complete state of the atmosphere at a particular instant in time and with the evolution of this state through the generation, growth and decay of individual disturbances.

- Climate is the synthesis of weather over the whole of a period essentially long enough to establish its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state.
- Climate Change defines the difference between long-term mean values of a climatic parameter or statistic, where the mean is taken over a specified interval of time, usually a number of decades.
- Climatic Variability includes the extremes and differences of monthly, seasonal and annual values from the climatically expected value (temporal mean). The differences are usually termed anomalies.

1.3 Components of the climate system

The climate system consists of the following components:

- The Atmosphere is the most variable part of the system. The troposphere has a characteristic response or thermal adjustment time of the order of one week while the stratosphere and higher layers of the atmosphere have quite different processes and time scales.
- The Oceans in the upper layers interact with the overlying atmosphere or ice on time scales of months to years, while the deeper ocean has a thermal adjustment time of the order of centuries.
- The Cryosphere, which comprises the world's ice masses and snow deposits, includes the continental ice sheets, mountain glaciers, sea ice and surface snow cover. The changes of snow cover and the extent of sea ice show large seasonal variations while the glaciers and ice sheets respond much more slowly.
- The Land Surface is here taken to comprise the land masses of the continents, including the mountains and plains, surface rock, soil and vegetation as well as the lakes, rivers and ground water which are important components of the hydrological cycle. They are variable parts of the climate system at all time scales. The earth's surface is an important source of airborne particulates which may be of climatic significance. The soil, in turn, evolves in response to climate and vegetation.

Life on earth is found on land (terrestrial biota), in the sea (marine biota) and in the atmosphere. The biosphere is the collective term for this part of our environment within which living and dead organic matter is present.

1.4 Time and space scales

A WCRP should be primarily concerned with time scales from several weeks to several decades. However, the ensemble properties of individual weather events with characteristic time scales of less than several weeks, such as synoptic disturbances, are included. The general limitation to several decades is consistent with the

availability of comprehensive data sets, the practicalities of numerical modelling and the major concern of planners and decision makers. Some requirements such as paleoclimatic reconstructions will undoubtedly involve larger time scales.

A WCRP should be primarily concerned with space scales from regional, of about 1 000 km, up to global. The emphasis on these larger scales is consistent with the technical limitations on climate modelling and the correlation scale of climatic anomalies. It is recognized that small scale processes can play a significant role in climate. An understanding of these processes and the parameterization or representation of their effects in models is an important research problem.

Conversely, in the final analyses, many applications of climate information, both empirically or theoretically derived, can be used for local decision making. It is therefore desirable to develop methods making it possible to interpret large scale climatic information on the appropriate smaller scale.

It is recommended that climate studies, both of real data and of model simulations, should focus not only upon averages but upon the characteristics of variations about these averages, including the probabilities of the occurrence of rare or extreme events.

2. RESEARCH ELEMENTS

In the following sub-sections we identify and discuss briefly six categories of research or effort which are necessary for the development of an effective climate research programme.

2.1 Climate diagnostics

A comprehensive quantitative description of the earth's climate is an essential foundation for research. The simpler statistics, viz., means, variances and to some extent covariances are fairly well known for the basic variables. However, there is a need for a more complete statistical description of the climate than is presently available. This should include the determination of the higher statistical moments which would aid the study of the responses to perturbations of the climate system.

Furthermore, the statistical description of the atmospheric climate needs to be supplemented by a corresponding one for the oceans, although here the difficulty of obtaining sufficient data will be severe.

Studies of physical processes inter-relating atmospheric variables and parameters external to the atmosphere (e.g., solar input, snow/ice cover, ocean temperatures, etc.) would be essential to elucidate what part of the observed variability arises from quasi-random internal fluctuations and what part is due to variations in the external forcing.

Apart from statistical diagnostics, some synoptic/empirical studies should be pursued especially to study the tendency of the atmosphere to undergo sudden shifts in its behaviour, e.g., sudden changes in the track of cyclones, the sudden onset of blocking, etc.

2.2 Climate model development

Climate models are developed for the purpose of describing in a quantitative manner the various physical, chemical and biological processes in the climate system which collectively determine the climate.

Numerical models for the study of many aspects of the behaviour of the global atmosphere provide a well established research tool, and undoubtedly they will play a major part in the study of climate and its sensitivity to human influences. However, for climate research the demands on the models will in certain respects be much greater than has been the case in the past. In particular the parameterization problems will be more wide ranging and of greater difficulty.

The development of models is not simply a means to an end; it is a central organizing and co-ordinating process within climate research as a whole.

The modelling research community will need to employ a hierarchy of modelling approaches ranging from those of the full general circulation models or coupled ocean/atmosphere models to simpler models which do not attempt time integration of the full three-dimensional system. The simpler models call for a higher level of parameterization, but where this can be achieved successfully they provide a means of gaining useful insight for the expenditure of smaller computing resources. Laboratory models may also have a part to play and should not be neglected.

All of the models will need the data base discussed earlier to aid their design and for validation purposes (see Report on Climate Data).

2.3 Climatologically significant processes

Many processes in and among the components of the climate system may influence the climate. Among these the following require special attention:

2.3.1 Ocean processes

The oceans play a key role in the global heat balance through storage and transport of heat and should be taken into account in any programme which attempts to describe or predict climate or climate variability. Consequently, the development of a climate programme should be integrated with an ocean programme which seeks to observe, understand, model and predict those processes in the ocean that play major roles in the climatic interaction of ocean and atmosphere.

Within the time scales of months to years ocean-atmosphere interactions are, for the most part, limited to the upper few hundred metres of the oceans. The most active interactions occur in the low latitude areas where the planetary jets (e.g., Gulf Stream and Kurashio currents) originate, in the zones of unstable stratification, at the ice-edge, in regions of upwelling, and in zones of monsoon formation. For the purpose of climate prediction, it will be necessary to design a system of monitoring of the upper layers and to develop further viable techniques of observation. The observational system should be designed to make use of and to provide data for combined thermohydrodynamic models of the ocean and atmosphere.

Attention should also be given to the poleward heat flux and its incorporation into global climate models, and to the transport of heat from one region of the ocean to the other which fluctuates considerably due to open ocean eddies. Furthermore, it should be noted that the change in ocean albedo which might arise from a change in biological productivity could have a significant effect on global climate.

At the longer time scales of tens of years to centuries, account must be taken of the abyssal circulation of the ocean and the processes leading to the sinking of water to greater depths in the polar regions. The problems involved will have to remain in the realm of research for the present due to the difficulty of observation.

A relatively complete understanding of the climate system cannot be achieved without an understanding of the influence of sea ice which will involve, for example, investigations of the extent of sea ice in the Arctic and Antarctic, the existence of polynyas, and other phenomena which affect heat exchange. The ice problem is complex, involving ocean currents, and will only be solved by successful modelling based upon observation.

2.3.2 Biogeochemical cycles

Certain trace gases can influence the climate through their effect on radiative transfers and therefore must be considered. They include carbon dioxide, ozone, oxides of hydrogen, nitrogen and chlorine type compounds. To provide a capability of forecasting the future level of such constituents in the atmosphere as a consequence of human activities there is need for intensified research on the dynamics of biogeochemical cycles and their interaction. One requirement must clearly be to monitor the concentration of such gases present in the atmosphere, and the adequacy of existing monitoring therefore needs to be reviewed.

2.3.3 Clouds and their radiation processes

Clouds play a central role in determining the balance between the incoming short wave and the outgoing long wave radiation. Calculation of the complex radiative effects is in principle possible but this is hampered by an inadequate knowledge of the distribution of clouds and of their optical/radiative properties. For use in future climate models there will be a requirement for better empirical relations between cloudiness and the explicit model variables.

2.3.4 Aerosols and their various impacts

These can influence the climate through their direct effect on radiative transfers or indirectly through their effect on the formation and properties of clouds. They can be natural or man-made, e.g., industrial. We need to identify the important aerosol types and determine their climatological distribution. We need then to investigate by model experiments the relative importance of aerosol effects as compared with other physical effects.

2.3.5 Hydrological cycle

The hydrological cycle provides a dominant energy source for driving the motions of the atmosphere. Therefore it is required to study the components of this cycle, such as precipitation, evaporation, soil moisture, run off, etc., on a global scale.

2.3.6 Land surface and cryosphere processes

Numerical experiments show that regional albedo and soil moisture changes may significantly affect climate. However, although the model experiments have been revealing, the models require better treatments of albedo, evaporation, evapotranspiration, surface friction and snow/ice cover. The design of improved formulations for these land surface effects is rendered difficult by the marked inhomogeneities on sub-grid scales.

It is understood that interaction processes between the atmosphere and the cryosphere should be taken into account when modelling the climate system. Therefore, it is recommended that the energy exchange between snow and ice and the atmosphere be investigated.

2.3.7 Sun-earth investigation

It is recommended that a quantitative evaluation be made of the influence of solar activity on climate. The role of the interaction processes in the upper and lower atmosphere in climatic variations needs to be assessed.

2.4 Climate predictability

Although a large part of climate variability on time scales up to a few months is the composite effect of weather systems which are only individually predictable for a week or so, there is a reasonable expectation that some features of the variability may be predictable for much longer, e.g., the tracks of cyclones, the incidence of blocking, some aspects of the monsoon, etc. The requirement is therefore to test the capability of models to predict significant features of atmospheric variability over periods of time ranging from several weeks to decades. This should include the influence of slowly varying components of the climate system.

2.5 Climate sensitivity

Here we are concerned with experiments to assess the sensitivity of the climate to changes in the following conditions:

- (a) Boundary conditions (solar radiation, albedo, phenomena of the ocean-atmosphere interface, vegetation, etc.);
- (b) An atmospheric constituent (carbon dioxide, ozone, aerosols, chlorofluoromethanes, etc.).

Such studies will include most of those bearing on the effect of human influences on climate.

2.6 Long-term climatic trends

It is recommended to assess and analyse the long-term trends in variability of the modern climatic regime using the best available sets of data on climate of the previous century and the last millennia.

It should be stressed that paleoclimatic studies should be expanded, since they provide a basis for such assessment and for other climate prediction research including possible scenarios. Modern geomorphological, paleogeographic biological methods should be further developed.

3. DATA REQUIREMENTS FOR CLIMATE RESEARCH

Apart from the data needed to establish the statistical diagnostics discussed in 2.1, data are required for a variety of other purposes in climate research (see also the Report on Climate Data). Thus:

- (a) Parameterization. Climate models will in general require that certain physical processes can be taken into account only in a statistical sense; the design of some of these parameterization schemes may require special observations programmes on appropriate space and time scales.
- (b) Verification. The data base generated by the global observing system, which exists for general purposes including weather prediction, will probably suffice for the verification of the results from climate models. However, its adequacy for this purpose requires study. Furthermore, paleoclimatic reconstructions provide an important and unique validation of the ability of climate models to reproduce the very large swings of terrestrial climatic regime known to have occurred.

4. SCIENTIFIC PRIORITIES

The following specific topics should receive high priority in the WCRP. They have been identified as scientifically tractable and of fundamental importance in climate research:

- (a) Observational synthesis of the global and regional climate system (see 2.1);
- (b) Development of a hierarchy of models to study the dynamics and statistics of global and regional climate (see 2.2);
- (c) The role of the oceans in the climate system (see 2.3.1);
- (d) Biogeochemical cycles of radiatively important trace gases (see 2.3.2);
- (e) Cloud formation, distribution and radiative properties (see 2.3.3);

- (f) Aerosol types, optical properties and influence on clouds (see 2.3.4);
 - (g) The hydrological cycle, evaporation and precipitation, etc. (see 2.3.5);
 - (h) Land surface and cryosphere properties and processes and their impacts on climate (see 2.3.6);
 - (i) Paleoclimatic reconstructions relevant to global and regional climate changes (see 2.3.7).
-

PROGRAMME OF THE WORLD CLIMATE CONFERENCE (WCC)

Honorary President: Dr. D. A. Davies

Chairman: Dr. R. M. White

Monday, 12 February 1979

Morning Session A Chairman: D.A. Davies, Secretary-General
World Meteorological Organization

Opening Ceremony - Statements:

Dr. D.A. Davies, Honorary President of the Conference;
Secretary-General of the World Meteorological Organization.

Dr. K.K.S. Dadzie, Director-General for Development and International
Economic Co-operation, United Nations.

Dr. H. Mahler, Director-General, World Health Organization

Dr. M.K. Tolba, Executive-Director, United Nations Environment
Programme.

Dr. R.W. Phillips, Deputy Director-General, Food and Agriculture
Organization of the United Nations.

Mr. F. Mayor, Deputy Director-General, United Nations Educational,
Scientific and Cultural Organization.

Sir John Kendrew, Secretary-General, International Council of
Scientific Unions.

Dr. O. Vasiliev, Deputy Director, International Institute for
Applied Systems Analysis.

Keynote Address - Climate at the Millenium - R.M. White, U.S. National
Academy of Sciences, Washington, D.C., U.S.A.
Conference Chairman

Climatic Change and Human Strategy - E.K. Fedorov, State Committee for
Hydrometeorology and Control of Natural Environment, Moscow, U.S.S.R.

Afternoon Session B Chairman: A. Villeveille, Etablissement d'études et de recherches météorologiques, Boulogne-Billancourt Cedex, France.

1. Global Ecology and Man - B. Bolin, Unesco Consultant, Department of Meteorology, University of Stockholm, Sweden. Paper sponsored by Unesco.
2. Climatic Variation and Variability, Empirical Evidence from Meteorological and Other Sources - F.K. Hare, Institute for Environmental Studies, University of Toronto, Canada.
3. Climates of Past Geological Epochs - E.P. Gerasimov, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

Tuesday, 13 February 1979

Morning Session C Chairman: G.O.P. Obasi, WMO Secretariat, Geneva

1. The Physical Basis of Climate - W.L. Gates, Department of Atmospheric Sciences, Oregon State University, Corvallis, Oregon, U.S.A.
2. Modelling of Climatic Changes and the Problem of Long-Range Weather Forecasting - G.I. Marchuk, Central Computing Centre, Siberian Academy of Sciences, Novosibirsk, U.S.S.R.
3. Some Results of Climate Experiments with Numerical Models - B.J. Mason, Meteorological Office, Bracknell, Berkshire, U.K.

Afternoon Session D Chairman: W.J. Gibbs, Blackburn, Victoria, Australia

1. Climate Monitoring and Climatic Data Collection Services for Determining Climatic Changes and Variations - Ju. A. Izrael, State Committee for Hydrometeorology and Control of Natural Environment, Moscow, U.S.S.R.
2. Human Activities that Affect Climate - R.E. Munn, Institute for Environmental Studies, University of Toronto, Canada, and L. Machta, Air Resources Laboratories, National Oceanic and Atmospheric Administration, Washington, D.C., U.S.A.

Tuesday, 13 February 1979 (cont.)

Afternoon Session D

3. A Scenario of Possible Future Climates, Natural and Man-Made -
H. Flohn, Meteorological Institute, University of Bonn,
Federal Republic of Germany

Wednesday, 14 February 1979

Morning Session E Chairman: R.Revelle, Department of Political Science,
University of California, San Diego, U.S.A.

1. Energy and Climate: A Review with Emphasis on Global Interactions -
J. Williams, W. Haebele, W. Sassin, Energy Systems Program,
International Institute for Applied Systems Analysis, Laxenburg,
Austria.
2. Climate Variability and the Development and Management of Water
Resources - J.C. Schaake, Jr., Hydrological Research Laboratory,
National Oceanic and Atmospheric Administration, Silver Spring,
Maryland, U.S.A.; and Z. Kaczmarek, Institute of Meteorology and
Water Management, Warsaw, Poland.
3. Climate, Health and Disease - W.H. Weihe, Temporary Advisor to the
World Health Organization, Central Biological Laboratory,
University of Zurich, Switzerland. Paper sponsored by WHO.

Afternoon Session F Chairman: W. Baier, Agrometeorology Research and Service,
Chemistry and Biology Research Institute,
Ottawa, Canada.

1. Global Aspects of Food Production - M.S. Swaminathan, Indian Council
of Agricultural Research, New Delhi, India.
2. Climatic Variability and Agriculture in the Temperate Regions -
J.D. McQuigg, FAO Consultant, Consulting Climatologist, Columbia,
Missouri, U.S.A. Paper sponsored by FAO.
3. Study on the Climatic Change and Exploitation of Climatic Resources
in China - Chang Chia-cheng, Academy of Meteorological Science of
Central Meteorological Service, Peking, China; and Wang Shao-wu,
Peking University, Peking, China; and Cheng Szu-chung, Geographical
Institute of Academia Sinica, Peking, China.

Thursday, 15 February 1979

Morning Session G Chairman: F. Hashemi, Quanta Consulting Engineers, Tehran, Iran.

1. Climatic Variability and Agriculture: Semi-Arid Tropics - F. Mattei, FAO Consultant, National Research Council and Central Office of Agricultural Ecology, Rome, Italy. Paper sponsored by FAO.
2. Climatic Variability and Agriculture in Tropical Moist Regions - H. Fukui, FAO Consultant, Centre for Southeast Asian Studies, Kyoto University, Japan. Paper sponsored by FAO.
3. Renewable Resources and Agriculture in Latin America in Relation to the Stability of Climate - J.J. Burgos, University of Buenos Aires and National Council of Scientific and Technical Research, Buenos Aires, Argentina.

Afternoon Session H Chairman: A.F. Treshnikov, Institute for Arctic and Antarctic Research, Leningrad, U.S.S.R.

1. Climatic Variability and Land Use: An African Perspective - J. Oguntoyinbo, Department of Geography, University of Ibadan, Nigeria; and R.S. Odingo, Department of Geography, University of Nairobi, Kenya.
2. Climatic Variability and Forestry - A. Baumgartner, FAO Consultant, Department of Bioclimatology and Applied Meteorology, University of Munich, Federal Republic of Germany. Paper sponsored by FAO.
3. Climatic Variation and Marine Fisheries - D.H. Cushing, FAO Consultant, Fisheries Laboratory, Ministry of Agriculture, Fisheries and Food, Lowestoft, Suffolk, U.K. Paper sponsored by FAO.

Friday, 16 February 1979

Morning Session I Chairman: V.A. Kovda, Agrochemistry and Pedology Institute, Moscow, U.S.S.R.

1. Climatic Variability, Marine Resources and Offshore Development - T. Gaskell, Unesco Consultant, Oil Industry International Exploration and Production Forum, London, U.K. Paper sponsored by Unesco.

Friday, 16 February 1979 (cont.)

Morning Session I

2. Climate and Economic Activity - R. d'Arge, Department of Economics, University of Wyoming, Laramie, Wyoming, U.S.A.
3. Climate and Society: Lessons from Recent Events* - R.W. Kates, Graduate School of Geography, Clark University, Worcester, Massachusetts, U.S.A.

Afternoon Session J Chairman: R.M. White, U.S. National Academy of Sciences, Washington, D.C., U.S.A.

Plenary, Session Chairmen presentations, discussion.

Organization of Working Groups

I. Climate Data and Applications

Co-chairmen: R. Czelnai, Meteorological Service of the HPR, Budapest, Hungary.
H.E. Landsberg, Institute for Physical Science and Technology, University of Maryland, College Park, U.S.A.

II. The Influence of Society on Climate Change and Variability

Co-chairmen: A.E. Collin, Atmospheric Environment Service, Downsview, Canada.
W.J. Maunder, New Zealand Meteorological Service, Wellington, New Zealand.

III. Impacts of Climate Change and Variability on Society

Co-chairmen: S. Ichimura, Centre for Southeast Asian Studies, Kyoto University, Japan.
J.C.I. Dooge, Department of Civil Engineering, University College, Dublin, Ireland.

IV. Research on Climatic Change and Variability

Co-chairmen: Ju.S. Sedunov, State Committee for Hydrometeorology and Control of Natural Environment, Moscow, U.S.S.R.
A. Wiin-Nielsen, European Centre for Medium-Range Weather Forecasts, Bracknell, Berks, U.K.

* This overview paper was prepared during the Conference at the request of the Bureau of the Organizing Committee as a replacement for an originally scheduled paper.

Schedule of Working Groups

Monday, 19 February	a.m.	Plenary Session Working Groups I and IV
	p.m.	" " II and III
Tuesday, 20 February	a.m.	" " I and IV
	p.m.	" " II and III
Wednesday, 21 February	a.m.	" " I and IV
	p.m.	" " II and III
		Plenary Session
Thursday, 22 February	a.m.	Plenary Session
	p.m.	Preparation of reports
Friday, 23 February	a.m.	Final meetings of all working groups
	p.m.	Plenary Session

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