POLICY-ORIENTED IMPACT ASSESSMENT OF CLIMATIC VARIATIONS

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RR-87-7
June 1987

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

International Standard Book Number 3-7045-0083-6

Executive Summary

Variations in the Earth's climate have significant impact throughout society. Policy actions either to deal with their effects or to prevent changes require concise information about the nature and timing of the effects at local, regional, and global levels. Although the ability of the scientific community to provide information on effects has increased greatly in recent years, many gaps and weaknesses in our knowledge remain.

This discrepancy between policy needs and research outputs was the focus of a three-day Task Force meeting at the International Institute for Applied Systems Analysis (IIASA), which was jointly supported by the United Nations Environment Program, the World Meteorological Organization, the Canadian Climate Center, the US National Climate Program Office, and the Netherlands' Ministry of Housing, Physical Planning, and Environment. Twenty-four invited participants from 14 countries joined with IIASA staff and other institutional observers to discuss recent progress in climate impact assessment in the light of policy needs.

Building upon a 1985 World Climate Program Conference at Villach, the group developed specific recommendations regarding future policy-relevant research in the areas of climate scenario development, agriculture, water resources, marine fisheries, and forests and tropical biomes. Special emphasis was given to the need to integrate sectoral studies at the regional level and to examine interactions between climate-induced effects and other pressing policy problems, such as international migration, resource depletion, and economic development in the tropics. The group strongly emphasized the need for continuing, close interaction between the scientific and policy communities, including policy makers and their advisors, climate modelers, impact assessors, and sector-specific experts.

A summary of the principal conclusions of the meeting in seven subject areas follows.

(1) *Climate scenarios.* Currently available predictions of future climatic conditions are quite limited in their reliability, resolution, and realism. Hypothetical scenarios of possible future climatic conditions are therefore indispensable inputs into any detailed assessments of effects. *Further development and refinement of climate scenarios is both possible and desirable.* This work, although carried out primarily by atmospheric scientists, could be made more useful if it received guidance from both the impact and policy communities. High-priority tasks include:

  (a) Development and refinement of links between the large-scale outputs provided by general circulation models (GCMs) and the smaller-scale inputs required by crop–yield models, basin-level hydrological models, and other impact assessment methods.
  (b) Construction of scenarios for selected regions based on GCM, instrumental, and/or other empirical data, including regions such as the tropics where GCM performance is less reliable.
  (c) Preparation of guidelines for the "baseline" used in climate scenarios, the varying uncertainty associated with different parameters and regions, and the intercomparison of scenario experiments.
  (d) Development of proposals for new scenarios other than the basic "doubled CO_2" equilibrium run typically produced by GCMs, where possible at finer time and space scales, encompassing a more complete set of local and regional climatic parameters and their time-dependent statistical properties, and reflecting a range of possibilities and uncertainties.

(2) *Agriculture.* Climatic variations affect agricultural activities in numerous ways and with many repercussions both inside and outside of the agricultural sector. This underscores the need to closely couple crop, livestock, and other biophysical responses with economic and social effects at the farm and regional levels. Careful linking of biophysical, farm-level, and regional economic models provides a practical method for characterizing key sensitivities, feedbacks, and policy alternatives for the agricultural sector as a whole. Further work on improving model linkages and on developing greater model integration is clearly needed. Specific recommendations include:

  (a) Identification and improvement of minimum, baseline data sets of key physical, biological, economic, and social variables for multisectoral analyses, including efforts to upgrade their spatial and temporal resolution.
  (b) Development of generic models for a much wider range of species and production systems than now available.
  (c) Analysis of historical situations to provide insights into cause-and-effect relationships and the range of available adjustment processes on local and regional scales.
  (d) Investigation of the past and potential future impact of carbon dioxide enrichment, sea level rise, and hydrological changes on agricultural systems.

(3) *Water resources.* Present-day water systems already take a high degree of climatic variability into account to protect against extremes. However, long-period climatic variations may significantly decrease safety margins and threaten the physical and institutional preparedness of the water sector. Special attention should therefore be given to:

(a) Assessment of the sensitivity of demand for water and water-related services to climatic effects on local and regional scales.
(b) Analysis of the physical, ecological, and socioeconomic implications of changes in the frequency and persistence of extreme events, such as floods and droughts.
(c) Case studies of water quality management in situations of climatic stress.
(d) Improved links between large-scale climate models and existing regional hydrological models.

The vulnerability to climatic variations of water projects currently in progress or being planned should be checked, especially those in developing countries or in areas where rapid population growth is expected.

(4) *Marine fisheries.* The effects of climatic variations on marine fisheries are complex and heterogeneous, varying greatly from species to species and from place to place. Significant effects in fish communities are likely to occur well before they become evident in commercial fishing and may be obscured by natural fluctuations. This makes the *direction* of changes, i.e., whether net fish populations will increase or decrease, difficult to predict with any certainty. In the near term, it will be important to develop:

(a) Empirical assessments based on "zoogeographical correlations", i.e., observed relationships between ocean climates and the spatial boundaries of marine fish populations.
(b) Reasonable predictions and scenarios of ocean climate parameters from coupled ocean–atmosphere models.
(c) Increased and long-term monitoring of marine ecosystems and associated habitats, especially in transitional zones.
(d) Definitions, classifications, and quantifications of marine species assemblages (communities) and habitats and their sensitivity to climate on regional and global scales.

In the long term, basic research on the mechanisms by which the environment affects fisheries is indispensable. The goal should be to develop credible global and regional assessments of effects in the medium and long term. In the meantime, however, the policy community needs to recognize that major climatic effects on marine fisheries are highly likely and should plan accordingly for versatility and resilience in their allocation of resources.

(5) *Forests and tropical biomes.* The time scale for climate-induced changes in forests and tropical biomes is likely to be generally comparable to the time scale of natural forest rotation and land-use changes, i.e., 50 years or more. This suggests that the initial focus for policy-oriented research should be on shifts in the boundaries between ecosystems – e.g., between boreal forests and tundra and between tropical forests and savannas – and their long-term implications. Specific concerns are possible changes in fire frequency,

increased oxidation of peatlands, and acceleration of deforestation due to climate-induced population migration. Promising research directions include:

(a) Analysis of shifts in ecosystem boundaries (e.g., tree lines and limits of vegetation zones) as a function of changes in climatic parameters.
(b) *In situ* studies, baseline studies, and model development as the basis for satellite-based remote sensing of changes in ecosystems, forest cover, fire frequency, erosion, and sedimentation.
(c) Examination of the potential effects of changes in fire and storm frequency in both managed and unmanaged forests.
(d) Study of the effects of changes in sea level and sedimentation rates on mangrove swamps and other coastal ecosystems.

(6) *Integrated regional assessments.* Environmental and socioeconomic systems are closely interrelated at the local and regional levels and are likely to be simultaneously sensitive to climatic variations in diverse ways. An *integrated* approach to the assessment of the impact of climate is therefore crucial to the development of *comprehensive* response strategies. A *regional* approach makes sense because a high degree of climatic homogeneity and close sectoral interconnections are often found at the regional level. Unfortunately, experience with integrated regional assessments is at present very limited, and the methods available are primitive. Research priorities therefore include:

(a) Identification of the salient sensitivities of and interactions between components of regional systems under various scenarios of climatic variation.
(b) Examination of the compatibility of analytical models used in individual sectors, such as agriculture, water resources, forestry, and energy consumption, and of methods for linking such models.
(c) Analysis of the distributional characteristics of impacts within regions and their implications for regional-scale institutions and policies.
(d) Exploration of the joint effects of climatic variations; demographic, environmental, and technological changes; and adjustment strategies.

Regional studies were proposed for North and South America, Europe, the Arctic, India, and Africa at the 1985 Villach Conference (World Climate Program, 1985). *It is important that these regional studies adopt an integrated assessment approach.*

(7) *Policy issues.* Climatic variations are likely to have important implications for many pressing, present-day policy issues. They could greatly exacerbate existing international problems such as international migration, transboundary pollution, disparate rates of development and population growth, unbalanced trade and capital flows, deforestation, desertification, and resource depletion. This underscores the need for *integrated* impact

assessment and response strategies at national and international levels. Such assessment studies need to address the full spectrum of climatic variations, impact, and response and their interaction with society. It is also necessary to convey the results of assessment studies to the policy community and the public and to provide continuing advice and guidance on alternatives and their implications. This suggests a number of useful activities:

(a) Analysis of the future evolution of anthropogenic perturbations to the climate and the biosphere and exploration of the feasibility of strategies to control or delay them.
(b) Identification of possible thresholds in impact and responses that might be associated with nonlinear or stepwise climate sensitivities.
(c) Exploration of methods to present scientific information on the impact of climate in a way that conveys the unavoidable uncertainties involved, yet preserves both the urgency of the issue and the credibility of the scientific community.
(d) Development of methods to assess the full sociopolitical implications of impact and responses, and their interactions with other policy issues at regional and global scales.
(e) Establishment of an international framework for assessing the risks and benefits of climatic changes and the effectiveness of alternative policy actions.

In these and related activities, increased and continuing interaction is needed among a wide range of participants from both market-oriented and centrally planned economies, developed and less developed countries, and the scientific and policy communities.

Foreword

Over many years, IIASA has undertaken internationally important studies in the climate field. The present phase, under the leadership of Dr. Martin Parry, currently at the University of Birmingham, UK, is nearing completion with the forthcoming publication of two books:

> Parry, M.L., Carter, T.R., and Konijn, N.T., *The Impact of Climatic Variations on Agriculture, Volume 1: Assessments in cool temperate and cold regions* (Reidel, Dordrecht).
>
> Parry, M.L., Carter, T.R., and Konijn, N.T., *The Impact of Climatic Variations on Agriculture, Volume 2: Assessments in semi-arid regions* (Reidel, Dordrecht).

Planning ahead, IIASA organized a Task Force Meeting (held in late June 1986) to undertake a policy-oriented assessment of various climatic impacts. Among the questions addressed were: What are the main policy questions and research needs in this field? Is there a niche for IIASA to fill meaningfully over the next several years? If so, should the work be an independent entity within the current Environment Program or should it be absorbed within the framework of other projects?

This report of the Task Force Meeting provides a focus not only for IIASA, but also for many other national and international bodies engaged in climate impact research. In particular, the idea of integrated regional assessments seems to have caught on, and this Research Report is likely to become a basic reference.

I am particularly grateful to the editors, Robert Chen and Martin Parry for their work in clarifying and synthesizing the findings of the Task Force. I also thank the participants and the cosponsors: UNEP, WMO, the Canadian Climate Center, the US National Climate Program Office, and the Netherlands' Ministry of Housing, Physical Planning, and Environment.

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Preface

The importance of improving the connection between policy needs and the outputs of climate impact research was recognized early in the development of the World Climate Program (WCP). In particular, the World Climate Impact Study Program (WCIP) was established with the objective "to insert climatic considerations into the formulation of rational policy alternatives" (World Meteorological Organization, 1980). Under the leadership of the United Nations Environment Program (UNEP), the WCIP was charged specifically with:

(1) Improving 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.).

(2) Developing our knowledge and awareness of the *interactive* relations between climatic variability and change and human socioeconomic activities.

(3) Refining the *methodology employed* so as to deepen the understanding and improve the simulation of the interactions among climatic, environmental, and socioeconomic factors.

(4) Determining the characteristics of human societies at different levels of development and in different natural environments that make them especially resilient to climatic variability and change and that also permit them to take advantage of the opportunities posed by such changes.

(5) Applying this new knowledge of techniques to practical problems of concern to developing countries or which are related to a common need for all mankind (World Meteorological Organization, 1980).

These objectives have led to an ambitious program of work. One major output has been an authoritative review of the methodology of climate impact assessment undertaken by the Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions (ICSU). This review highlighted the many pitfalls and limitations of existing techniques for assessing the impact of climate and sought to lay the groundwork for the development of new, interdisciplinary assessment methods (Kates *et al.*, 1985).

Another major effort of the WCIP is the IIASA Project on the Vulnerability of Food Systems to Climate. This project has involved over 70 scientists from around the world in a coordinated effort to examine the impact of climate in areas where agriculture is thought to be especially constrained by climatic factors. A basic premise of the study is that "sensitivity to climatic variability may be more readily observed (a) at the margin between two ecosystems (the *ecotone*), and (b) at the boundaries between different farming systems" (Parry and Carter, 1984: 3). Eleven case studies were selected from climatically "marginal" agricultural regions in high latitudes, at high altitudes, or in arid and semi-arid areas of the subtropics. For each study area, hypothetical "scenarios" of both climatic variability and change were used as inputs into existing physical models of crop growth, which in turn provided inputs for economic models of agricultural production (Parry *et al.*, forthcoming).

Despite the success of these and many other efforts to develop new approaches to climate impact assessment, there is still a large discrepancy between ***policy needs*** and ***research outputs.*** This discrepancy was noted at the recent International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts, held under the auspices of the WCP at Villach, Austria, in October 1985. The conference statement points out that:

> .... the understanding of the greenhouse question is sufficiently developed that scientists and policy makers should begin an active collaboration to explore the effectiveness of alternative policies and adjustments. Efforts should be made to design methods necessary for such collaboration. [World Climate Program, 1985: 3]

How to improve the connection between policy needs and research outputs was the focus of the Task Force Meeting on Policy-Oriented Assessment of Impact of Climatic Variations, held 30 June – 2 July 1986 at IIASA in Laxenburg, Austria. The objectives of the meeting were to:

(1) Identify the main policy issues and needs with respect to information from impact assessments of climatic variation and change.
(2) Determine the state of the art in the field of climate impact assessment by briefly reviewing recent developments, with particular reference to the provision of information useful to the policy maker.
(3) Make appropriate recommendations to improve information from climate impact assessments with respect to the needs of the policy maker and policy advisor.

An additional motivation for the meeting was to promote an active exchange of ideas between the policy and scientific communities at both national and international levels. The participants therefore included researchers, program officers, and policy advisors from developed and developing countries, centrally planned and market economies, national and international agencies, and governmental and nongovernmental organizations (see *Appendix A*).

To make the task more manageable, the meeting focused largely on the impact of climate on natural resources and associated effects and responses. We chose the areas of climate scenarios, agriculture, water resources, marine fisheries, and forests and tropical biomes as deserving the greatest attention in the light of both pressing policy needs and of recent progress in impact assessment. Reviews of the state of the art for each area were focused specifically on advances in methodology and applications since the preparation of the SCOPE report (Kates *et al.*, 1985). Special attention was also given to the concept of *integrated regional assessment* and to selected policy issues because of the need for further work noted at Villach (World Climate Program, 1985).

In addition, participants from various institutions concerned with developing or advising on climate policy issues presented short statements of their *perceptions* of policy needs for climate impact information. In most cases, these were not formal institutional statements, but rather constituted a cross-section of views by those who work within the institutions on a day-to-day basis. This informal information on policy needs was supplemented by preliminary results from a survey, conducted by UNEP, of the use of climate impact information by national governments.

This report summarizes the discussions at the meeting and the conclusions and recommendations developed by its working groups, drawing upon the draft statements prepared in each working group. Seven working groups covered the following topics: *climate scenarios, agriculture, water resources, marine fisheries, forests and tropical biomes, integrated regional assessment*, and *policy issues* (*Appendix B*).

We are most grateful to the United Nations Environment Program, the World Meteorological Organization, the Canadian Climate Center, the US National Climate Program Office, and the Netherlands' Ministry of Housing, Physical Planning, and Environment for their financial support, advice, and contributions at the meeting. We also appreciate the interest and contributions of the Organization for Economic Cooperation and Development, the Commission of the European Communities, the National Research Council of Italy, the Federal Office of the Environment of Austria, the US Environmental Protection Agency, the US Senate Committee on the Environment and Public Works, the International Meteorological Institute, and the World Resources Institute. We thank, first, all those who prepared the statements, scientific reviews, and commentaries that served as a common information base and stimulus to the meeting discussions, and second, those who chaired the sessions and working groups. Special thanks are due to Peter Usher of UNEP for his survey of national government needs. Marilyn Brandl and Lourdes Cornelio supplied able assistance in organizing the meeting and in preparing the report. Finally, we thank Ted Munn, leader of IIASA's Environment Program, for his guidance and encouragement.

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Appendixes:

POLICY-ORIENTED IMPACT ASSESSMENT OF CLIMATIC VARIATIONS

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1. Introduction

Awareness of the impact of climatic variations on human activities has expanded considerably in the past decade. Persistent drought in the Sahel and northeast Brazil, widespread forest fires in Australia and North America, outbreaks of locusts and other pests in Africa, extensive flooding in western South America, severe winters in Europe, and wide fluctuations in world food prices are just a few of the many adverse consequences of a highly variable and currently unpredictable climate. The possibility of climatic change, whether induced by natural or anthropogenic processes, raises the specter of even more frequent and severe impact in the future.

Our ability to deal with the impact of *present-day* climatic variability is limited at best. Droughts, floods, heat waves, cold spells, frosts, severe storms, and other climatic hazards exact a large toll every year in terms of human lives and livelihood. In part, this stems from our basic ignorance about the complex interplay between climatic factors and natural and human systems.

Our ability to deal with the impact of possible *future* climatic change will therefore be even more limited unless we can significantly extend our knowledge and broaden the range of practical policy responses. Climatic changes could include substantial alteration of growing seasons, precipitation patterns, temperature variability, storm tracks, windiness, sea levels, snow and ice volumes, and other aspects of the earth's climate. Such changes would undoubtedly have profound effects, both beneficial and adverse, on many human activities, including agriculture, water resource management, energy production, forestry, transportation, and fisheries.

Substantial progress has in fact been made in climate impact assessment over the past decade. More is now known about the vulnerability of different crops and cropping systems to climatic variability. Climatic data are now routinely incorporated into short-term energy demand estimates in many developed nations. A variety of methods for assessing the sensitivity of water supply to climatic variations have been explored. New satellite-based remote sensing techniques promise to improve significantly the spatial coverage and timeliness of many types of climate impact data.

However, major gaps and weaknesses remain. We know relatively little about the direct impact of climatic variability and change on subsistence crops, nonfood crops, plant pests and diseases, water demand, marine fisheries, soil erosion, forests, and tropical ecosystems. We know even less about their indirect impact on the world food market, regional food distribution, environmental degradation, resource depletion, international migration, comparative economic advantage, and economic development in the tropics. It is impact of this kind that is of primary concern to those involved in both short- and long-term decisions at local, regional, and global levels.

Moreover, the information needs of the policy community are increasing in both diversity and urgency. Growing awareness of the present-day influence of climate on different socioeconomic sectors has increased the need for timely and detailed climatic data in short-term planning and management. Growing awareness of the potential dangers of long-term climatic change has increased the need for information about the net costs and benefits of such climatic change in specific sectors and regions. Growing recognition of the high probability of long-period climatic fluctuations in specific regions has increased the need for new ideas on ways to decrease vulnerability and increase adaptability to climatic change.

Significant climatic fluctuations may be ongoing or imminent. The years 1980, 1981, and 1983 are reported to be the warmest for the globe as a whole in 134 years of record (Jones *et al.*, 1986). Evidence for a growing "hole" in the stratospheric ozone layer over the Antarctic has recently emerged from both ground- and satellite-based data (Farman *et al.*, 1985; Heath *et al.*, 1985; Krueger *et al.*, 1985; Tuck, 1986). Climatic extremes throughout the tropics and in some temperate zones have been associated with the so-called "El Niño–Southern Oscillation" phenomenon, which recurs at intervals of 2 to 10 years. [The El Niño, or "Christ Child", refers to a warm, nutrient-poor ocean current in the eastern Pacific Ocean that occasionally shifts southward to near the coast of Peru, usually arriving during the Christmas season. The Southern Oscillation refers to large fluctuations in atmospheric pressure, observed at many Southern Hemisphere stations, that reflect major changes in atmospheric circulation. In recent years, scientists have noted the close connection between these two seemingly disparate phenomena and have developed theories to explain their interrelationship.] These examples underscore the urgency of the need for policy information on the impact of climate that can be used in present-day decisions at local, regional, and global levels.

This report considers the principal needs of the policy community with respect to information from climate impact assessments. It highlights recent advances in methods of impact assessment, assesses the degree to which these advances meet policy requirements, and identifies future research priorities to meet policy requirements more closely.

2. Policy Needs at National and International Levels

It is a basic premise of this report that research on the impact of climate should be *guided* by policy needs. Climate impact assessment is a nascent field. The unknowns are many, but resources – time, money, and personnel – are limited.

Careful selection among the many possible choices for future research is therefore required to ensure that research outputs meet the needs of those who can use them in beneficial ways.

At the same time, research efforts should not be *constrained* by policy needs. That is, impact researchers should not confine themselves to traditional approaches and methods, but should think creatively about the kind and form of information that could be useful. For example, three hypotheses have been suggested *vis-à-vis* developing more "usable knowledge" about climatic variations and their impact:

(1) *The evaluation of first-order limits is more useful than the evaluation of second- and third-order effects.* For instance, if it is found that many natural and human systems do not respond linearly to climatic perturbations, it would be more important to determine whether there are significant thresholds and limitations in their response capabilities than to evaluate "downstream" effects.

(2) *Predictions of "not unlikely" futures are more valuable than prediction of the "most likely" future.* There has been a tendency to restrict assessments of climate impact to those changes in climate considered the most likely to occur. This has focused our attention on a small number of scenarios that, given our present very limited ability to predict climatic change, have only a small likelihood of actually occurring. It may be more sensible to consider a wider range of 'not unlikely' scenarios in order to capture the full array of possible futures.

(3) *Increasing the range of policy responses is more useful than refining existing response mechanisms.* Human systems already include many ways of responding to climatic variability. However, new mechanisms and responses may be necessary to deal with climatic changes that, combined with other environmental and social changes, present an unprecedented challenge to society.

These hypotheses can only be tested by actually generating examples of policy information of this kind and seeing if, in practice, they meet policy needs more closely than traditional methods. To do this, it is necessary to establish these needs more precisely. Policy needs at national and international levels are discussed in the following sections.

2.1. National needs

It is at the national level that key policies regarding agriculture, water, energy, land use, etc., are generally set and where the most practical opportunities exist for making decisions to prevent or adapt to climatic changes. Conventional wisdom, and the available evidence, suggest that there is a basic distinction between policy needs perceived by developing and developed nations. Developing nations are generally preoccupied with the immediate, short-term effects of climatic variability, e.g., droughts and floods. Developed nations, while concerned about near-term climatic variations, also view possibilities for future climatic change with concern. These nations normally have well-established institutional mechanisms for dealing with recurrent climatic events and episodes, such as severe storms, droughts, floods, and severe winters. A key issue for them, therefore, is whether future change would require modification of existing institutional mechanisms for dealing with climate or the development of new ones.

Needs of developing nations

The impact of climatic hazards in developing nations is staggering. In Africa, South America, and Asia, many countries are plagued by persistent and recurring drought, devastating floods and storms, damaging fires and frost, climatically-induced outbreaks of grasshoppers, locusts, and other pests, highly variable fisheries, and extensive desertification. At stake are the lives and livelihood of millions of subsistence farmers, the health and employment of tens of millions of urban dwellers, the sustainability of diverse ecosystems, and the solvency and integrity of national governments.

Effective actions at local, regional, or national levels to ameliorate the effects of climatic extremes require timely information on:

(1) The nature and expected frequency or persistence of the climatic hazard.
(2) Their likely impact on the environment, economy, and society.
(3) Policy responses and their likely effects.

Such information clearly requires data on a wide variety of phenomena, including (a) data on many different climatic parameters at time and space scales that match the time frames and spatial domains of subnational economic and political units; (b) data on both commercial and subsistence crops and on animal populations to assess the degree of possible food shortfalls in particular regions; (c) data on food prices and nutritional status to ascertain the distribution of food within populations; and (d) data on losses and damages for recovery measures and for future contingency planning.

Even if such data were available, their effective use in developing countries may be especially difficult because institutional mechanisms are lacking that can keep climatic considerations prominent in already overloaded policy agendas. In some instances, rapid turnover of policy makers and policy advisors makes the consistent development and implementation of long-run response strategies virtually impossible and increases the time required to educate the new leadership about problems and alternative solutions. As a result, policy makers often have to adopt emergency actions on very short time scales and with incomplete information on effects and alternatives. Such emergency actions may in fact damage long-run plans to improve resilience to climatic variability.

Information on the impact of climate is particularly crucial to the development of longer-term strategies to reduce vulnerability to climatic extremes and increase overall resilience. For example, Kenya managed to avoid widespread famine during the 1984 drought, the most severe since 1930, in part because large stocks of maize and wheat in the country in early 1984 gave the government sufficient time to import and distribute additional supplies. More complete and timely information on weather, major and minor crops, and food prices would, however, have assured earlier warning of the severity of the drought and its effects. Better planning of food stock levels, seed reserves, and livestock preservation and depletion could have reduced the costs of the drought. In the long term, information on the potential impact of climatic variations can help guide development efforts, for example, (a) to halt (or reverse) environmental degradation, including deforestation and desertification; (b) to develop adequate supplies of fresh water for human consumption, sanitation, and irrigation; and (c) to reduce variability in food production, especially that due to droughts, floods, and other climatic extremes.

Needs of developed nations

In contrast to developing nations, many developed nations have well-established mechanisms for mitigating the negative effects of climatic variations and for managing their climatic resources. These include environmental protection agencies, agricultural and rural development authorities, coastal development policies, and land-use regulations. Many nations also have mechanisms for long-term planning that can take climatic considerations explicitly into account.

More recently, some countries have established, or are in the process of establishing, national climate programs. These typically draw together programs of basic climatological research and monitoring with efforts to assess the impact of climate and to coordinate the incorporation of climatic considerations in governmental policies. An added function is often the provision of climate data and services to economic and social agencies.

In some instances, national climate programs have identified specific *regions* of interest. For example, the Canadian Climate Program has expressed special concern with the Great Lakes Basin, in which a large proportion of the Canadian population resides (Timmerman and Grima, 1985). The Netherlands' government has noted the extreme importance of possible climate-induced rises in sea level for the low-lying coasts of northern Europe (Health Council of the Netherlands, 1983, 1986). The proposed Italian Climate Program has highlighted the importance of the Mediterranean region to the climatology of the Italian peninsula.

Such programs and activities reflect the policy needs of developed countries for climate impact information. On the one hand, governmental organizations concerned with specific sectors want detailed impact information tailored to their individual institutional context and sectoral needs. On the other hand, governmental bodies with national or subnational jurisdictions require *integration* of impact information across sectors for their areas of concern. Moreover, since the effects of climatic variations are imbedded within other environmental and social issues, integrated *solutions* are generally needed. It may be necessary to accommodate these differing needs through a more comprehensive approach in which both "micro" sectoral methods and "macro" integrative methods are utilized and linked.

2.2. International needs

Climatic variations and their effects rarely coincide with national borders. Drought in the Sahel region of Africa has persisted for over a decade across thousands of kilometers and numerous nations. In 1982–1983 there was extensive flooding in North and South America, severe drought and wildfires in Australia, and failure of the monsoon in Indonesia and the Philippines. Droughts in the US Midwest have caused large fluctuations in world grain prices. Frosts in Brazil have sent shocks through the world coffee market.

The above examples underscore the growing interdependence of the modern world from both climatic and socioeconomic viewpoints. Through *atmospheric* "teleconnections" such as the El Niño and the Southern Oscillation, climatic extremes can occur simultaneously in widely separated parts of the globe. Through *economic* teleconnections, such as international trade in agricultural products and fossil fuels, the effects of climatic variations propagate around the world. Through the worldwide emission and spread of atmospheric trace gases, such as dioxide and methane, long-term global climatic changes may be under way or imminent.

Although most responses to climatic variations occur through national institutions and mechanisms, growing global interdependence suggests that international organizations, such as the specialized agencies of the United Nations, will need to play increasingly important roles in dealing with the impact of climate. In particular, such organizations will be critical in helping to generate the multinational awareness and consensus that will be necessary to overcome the wait-and-see attitude of many nations. This implies that international organizations need diverse policy-oriented information. Detailed regional analyses of the nature and timing of effects are needed to assist neighboring nations in developing coherent response strategies. Global assessments of long-term policy alternatives and possible outcomes are needed to advise world political leaders on proposed joint actions to avoid or mitigate climatic change. Retrospective studies are needed to elucidate the most effective approaches for encouraging regional and global cooperation in dealing with the impact of climate.

However, like many of their national counterparts, international organizations are highly compartmentalized. Their influence tends to be limited and their resources finite. Their direct constituencies are the national governments or organizations that comprise their formal membership. They tend to have relatively little contact with the multinational corporations, industrial associations, and financial institutions that are important actors in the international economic system. Research on the effects of climatic variations should, therefore, attempt to surmount normal institutional, disciplinary, and cultural boundaries.

3. Climate Scenarios

Modern computer-based models of the climate system are invaluable tools for investigating both present and future climatic variability and potential change. However, the reliability, resolution, and realism of their predictions are currently limited by uncertainties arising from inherent indeterminacy in the climate system, inadequacies in models, incomplete or erroneous input data, and other problems. In particular, the degree of reliability may decrease with increasing resolution, so that, for example, predictions for specific regions are likely to be less reliable than those for the globe, predictions for days and months less reliable than those for years, and predictions for evapotranspiration and soil moisture less reliable than those for temperature (National Academy of Sciences, 1982).

Nevertheless, it is precisely this sort of high-resolution information that is needed for most in-depth assessments of the impact of climatic variations. For example, daily data on temperature, solar radiation, and precipitation at a particular site are typically required as inputs into models of crop yield. Obtaining such data for the past and present is often difficult; obtaining reliable predictions of such data for the future is even more problematic.

An alternative method for providing this key link between climate and its impact is to develop hypothetical *scenarios* of possible future climatic conditions, i.e., "internally consistent and detailed specifications of climatic conditions over space and time" (National Academy of Sciences, 1982: 48). Such climate scenarios should have the overall statistical properties predicted by climate models or other methods and should, of course, exclude conditions believed to be impossible. However, they need not constitute formal predictions to which probabilities of occurrence are implicitly or explicitly assigned.

3.1. Recent progress

Many examples of climate scenarios, produced by a range of methods, are now available. Several different global general circulation models (GCMs) have been utilized to generate regional climate scenarios that include information on precipitation, soil temperature and moisture, and cloudiness. *Figure 1* is an example of the scenario output produced by the GCM of the Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University (Manabe and Wetherald, 1986; see also, Gates, 1985).

Analysis of the instrumental record of the past century for specific regions has yielded empirical scenarios based on (a) past occurrences of extreme warmth, cold, or variability (e.g., Wigley *et al.*, 1980; Namias, 1980; Williams, 1980; Lough *et al.*, 1983; Jäger and Kellogg, 1983; Parry and Carter, 1984; Wigley *et al.*, 1986) and (b) possible relationships between hemispheric temperatures and local climatic parameters (Vinnikov and Groisman, 1979). *Figure 2* illustrates an example of the former for Europe, in which climatic conditions for the warmest and coolest 20-year periods of the twentieth century are compared (Lough *et al.*, 1983). It may also be possible to utilize analogues from the more distant past, such as the warm period in the Holocene (6,000–9,000 BP) or the Little Ice Age in Europe (ca. 1600–1850 A.D.), using historical and paleoclimatic data to provide details on spatial and temporal patterns (e.g., Kellogg and Schware, 1981; Butzer, 1980; see also, Wigley *et al.*, 1986).

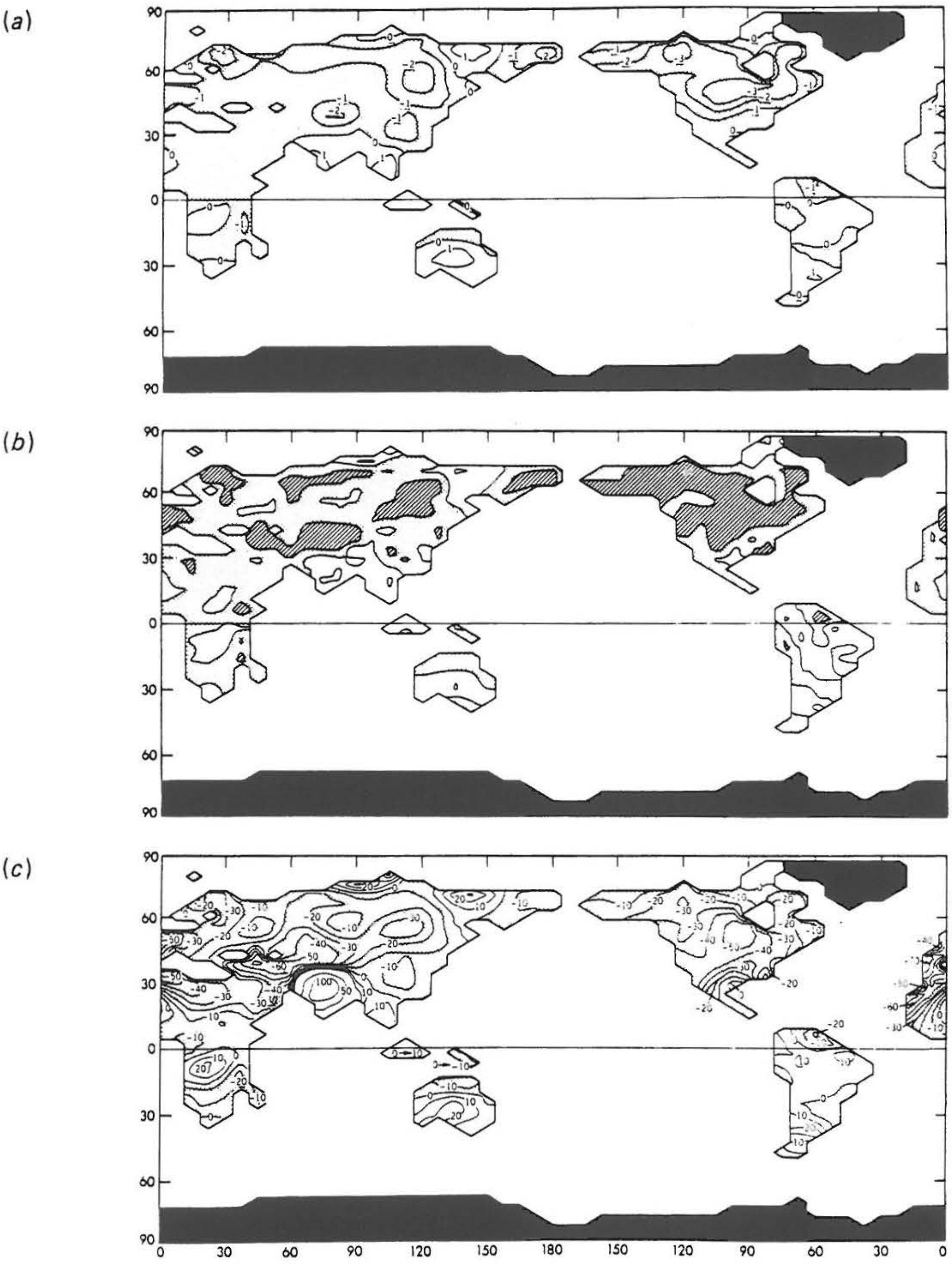


Figure 1. Scenario of soil moisture change for a doubling of CO_2 in the GFDL GCM. (*a*) Geographical distribution of soil moisture change (cm) for June to August. Shading indicates a negative change. (*b*) Statistical significance of the soil moisture change shown in (*a*). Line shading indicates statistically significant decreases at the 10% confidence level. (*c*) Soil moisture change expressed as a percentage of soil moisture obtained from the control experiment (normal CO_2). Source: Manabe and Wetherald (1986: p. 627; © 1986 by the American Association for the Advancement of Science).

Many, if not most, of the above scenario studies have focused on providing the regional and temporal detail for a warmer climate resulting from increasing atmospheric carbon dioxide and trace gases. However, climate scenarios may also be extremely useful inputs into studies of the impact of other types of climatic variability and change, whether natural or anthropogenic in origin. For example, in a set of case studies coordinated by Parry *et al.* (forthcoming), extreme cold and warm years and decades of the past (e.g., ***Figure 3*** for Iceland) were used to assess the sensitivity of present-day agricultural systems to climatic variability. Similarly, regional climate scenarios are considered critical inputs into efforts to assess the integrated impact of climate on geographical regions such as the Great Lakes (Timmerman and Grima, 1985).

3.2. Promising approaches

Despite many limitations, some scenario methods show considerable promise as starting points for policy-oriented assessment of climate impact. Further development and refinement of climate scenarios is both possible and desirable. Notably, this work, although carried out primarily by atmospheric scientists, could be made more useful if it received guidance from both the impact and policy communities. Some suggestions on directions for future work follow.

The further development of GCM-based scenarios would be especially useful for impact studies in a variety of areas. This endeavor should include empirically based attempts to make GCM-gridpoint output indicative of local- and regional-scale climate, a task that has been termed the "climate inversion" problem (Kim *et al.*, 1984; Gates, 1985). GCM scenarios have clear advantages for assessing the impact of possible long-term climatic changes induced by trace gas emissions.

Empirical scenarios based on observed data are likely to be more helpful for shorter time scales and for both short- and long-term climatic variations. In this context, they have not yet been produced for the tropical belt, an area for which GCM performance is less reliable than for higher latitudes. Such scenarios could also be improved on a regional basis by improving calibration with measures of global-scale climatic change such as the equator-to-pole temperature gradient and the mean global surface air temperature. Linkage of instrumental data to observed types of atmospheric circulation patterns, such as blocking events, may also be instructive.

Paleoclimatic analogue scenarios have weaker conceptual underpinnings and, therefore, may not be as useful. In particular, they assume that the general circulation of the atmosphere responds in a similar way to different forcing mechanisms (i.e., changes in the solar constant versus altered atmospheric absorption), given similar boundary conditions on land and in the oceans. However, this assumption is difficult to justify (Wigley *et al.*, 1986).

The possibility of developing a "geographical" scenario stratification requires further exploration. The basic concept here is that the present climate of one region may provide an analogy to the future climate of another region. For example, if warmer conditions were to develop in the future, southeast Iceland's

(a)

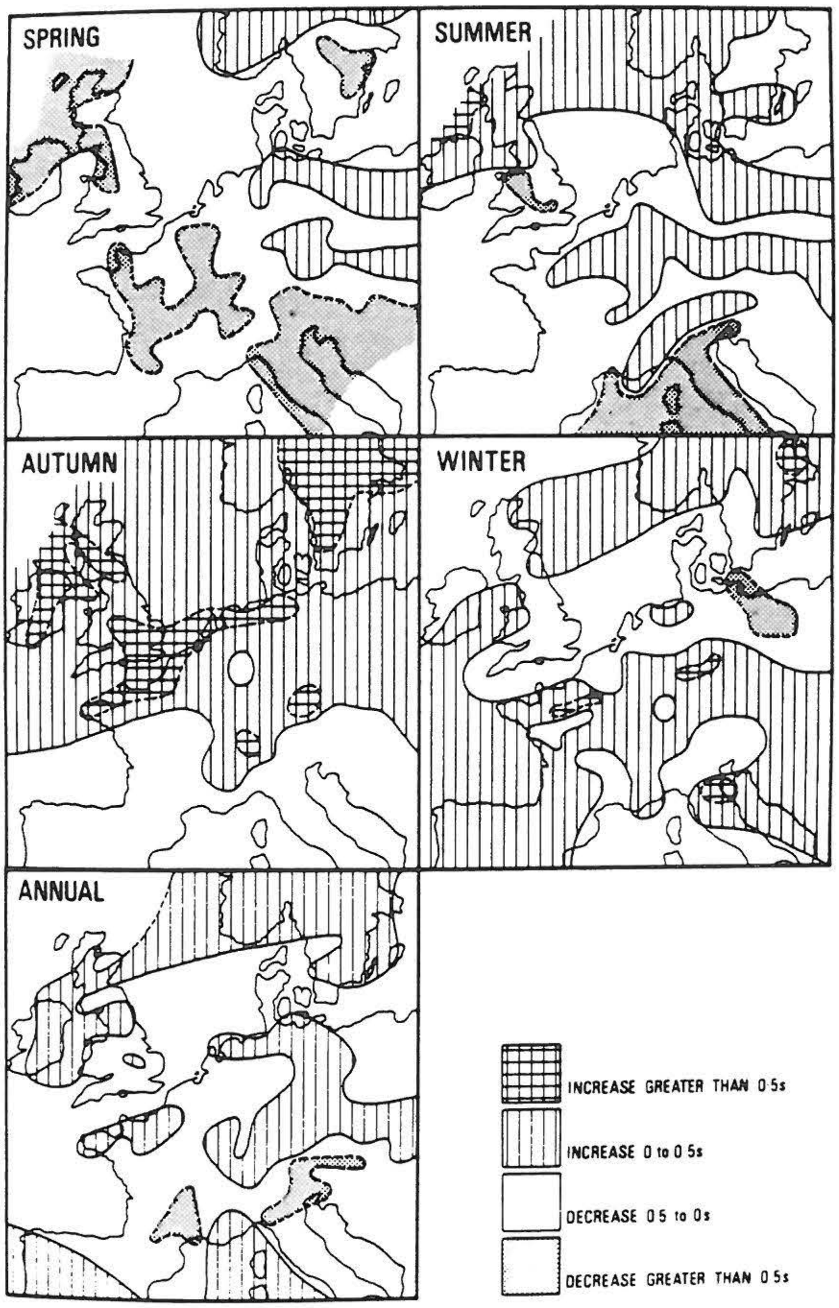


Figure 2. Scenario of climatic change in Europe based on the difference between the warmest 20-year period of the twentieth century, 1934–1953, and the coolest 20–year period, 1901–1920. Source: Lough *et al.* (1983); periods were selected based on the Northern Hemisphere time series of temperature developed by Jones *et al.* (1982). (*a*) Temperature differences (C), warm period minus cold period.

climate might become similar to today's climate in northeast Scotland (Bergthórsson *et al.*, forthcoming). This approach could shed light on the ability of society to adapt to altered conditions and should be helpful in conveying information at the policy level.

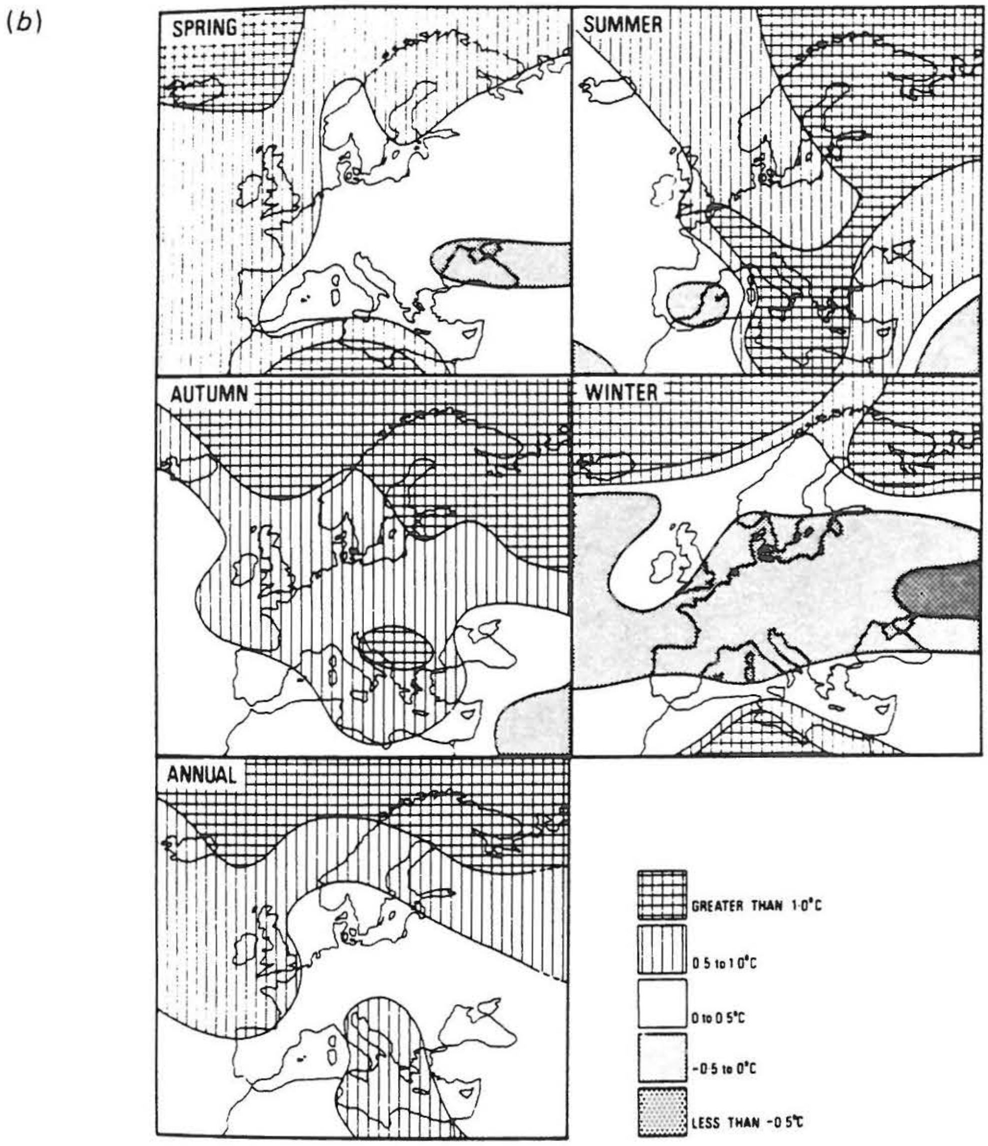


Figure 2 (*cont.*) (*b*) Precipitation change, warm period minus cold period, as multiples of the standard deviation.

Finally, more attention should be given to the development of scenarios for climatic variations of *natural* origin, especially for tropical regions. Although possible future climatic changes due to human activities are of serious long-term concern, present climatic variations, such as droughts, floods, and shifts in the monsoon, already have significant impact on society. Unfortunately, climatological observations in many areas are limited to only a few parameters, have low spatial and temporal resolution, and are of poor quality and short duration. This suggests that it may be necessary to use scenario techniques to develop a basic set of climatic inputs for studies of the impact of natural climatic variability.

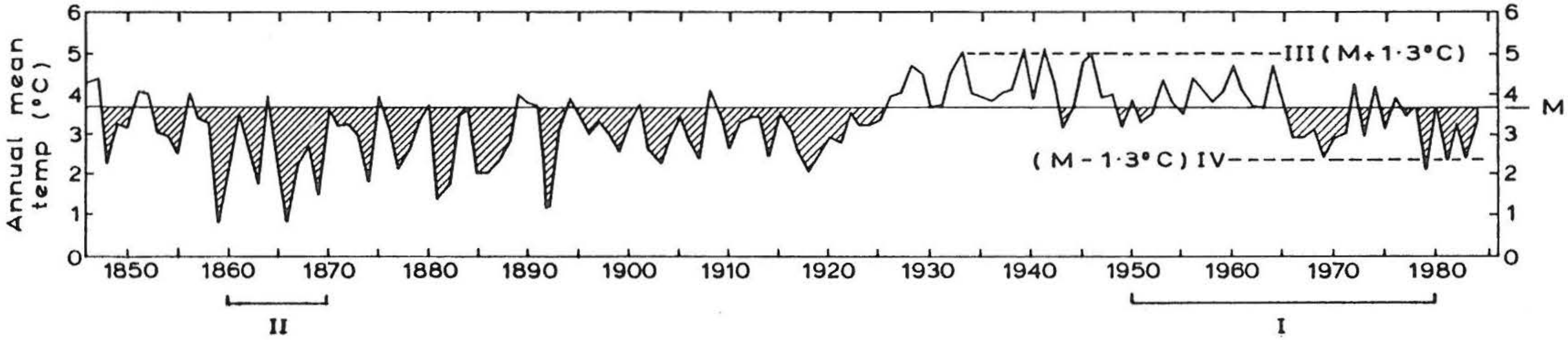


Figure 3. Alternative climate scenarios used in the Icelandic case study of the IIASA/UNEP Climate Impacts Project. The scenarios are derived from historical data for Stykkishólmur, Iceland (65°N) from 1846–1983. Scenario I is the reference or baseline scenario, based on the 30-year period 1951–1980. Scenario II is the coldest decade in the record, 1859–1868, and includes the two coldest years. Scenarios III and IV are based on the 10 coldest and warmest years (not necessarily consecutive) during the period 1931–1983; each scenario represents approximately a 1.3°C change from the long-term mean annual temperature. Scenario V uses the reference scenario as a base and adds the temperature increase predicted from the difference between the "doubled CO_2" and control experiments with the GISS GCM. Source: Bergthórsson *et al.* (forthcoming).

3.3. Recommended activities

Extensive research on the earth's climate system is now being conducted under the auspices of the WCP and various national climate programs. A major goal of this effort is to improve and validate GCMs and other climate models. If successful, such work would help overcome many of the present limitations of GCMs with respect to the development scenarios. Similarly, efforts now under way to expand and correct the instrumental record of the recent past will greatly assist the development of empirically based scenarios for different regions of the world.

In addition to these efforts, a number of specific tasks are recommended:

(1) *Development and refinement of links between the large-scale outputs provided by GCMs and the smaller-scale inputs required by crop-yield models, basin-level hydrological models, and other impact assessment methods.* This would use existing fine-scale observational data to develop "calibrations" applicable to future conditions. The possibility of imbedding local- or meso-scale models should also be pursued. Such links could include the computation of derived variables based on the primary outputs of GCMs.

(2) *Construction of scenarios for selected regions based on GCM, instrumental, and/or other empirical data, including regions such as the tropics where GCM performance is less reliable.* Initial efforts to develop climate scenarios have focused on large areas, such as Europe and North America, where data are relatively plentiful and GCMs appear to produce the most realistic results. While this was appropriate to demonstrate the feasibility of various scenario methods, climate scenarios for other regions, such as the tropics and the Sahel, are now needed as inputs into impact studies in these regions. Construction of such scenarios may entail extensive efforts to locate alternative data sources, combine differing scenario methods, and derive alternative parameters of special interest to particular regions.

(3) *Preparation of guidelines for the "baseline" used in climate scenarios, the varying uncertainty associated with different parameters and regions, and the intercomparison of scenario experiments.* Differing conventions in generating, presenting, and applying scenarios and the lack of information about uncertainty make the interpretation of scenarios and comparisons among them difficult. For example, clearer statements are needed about the baseline used in GCM-based scenarios (e.g., what reference observations and time period are used). Some indication of the degree of uncertainty associated with different parameters, latitudes, or regions (e.g., coastal versus interior) would assist in assessing the representativeness of alternative scenarios. Coordination of scenario experiments conducted on different GCMs would facilitate intercomparison and subsequent impact analysis.

(4) *Development of proposals for new scenarios other than the basic "doubled* CO_2*" equilibrium run typically produced by GCMs, where possible at finer time and space scales, encompassing a more complete set of local and*

regional climatic parameters and their time-dependent statistical properties, and reflecting a range of possibilities and uncertainties. Most GCM experiments to date have focused almost exclusively on the "equilibrium" climate resulting from an increase in atmospheric carbon dioxide concentrations to levels double (or quadruple) that of the "pre-industrial" level. They have tended to report only a small set of parameters (e.g., temperature and precipitation) at annual or perhaps seasonal intervals and with limited spatial resolution. The regional effects of alternative methods for handling key processes and variables (parameterizations) tend to be overlooked. Alternative climate scenarios are clearly required to meet differing needs. Given the expense of GCM experiments and other scenario efforts, proposals for alternative scenarios should incorporate inputs from impact researchers and others regarding specific parameters and outputs, spatial and temporal resolution, locations of special interest, and ancillary sensitivity studies. Coordination of these inputs should be part of the planning for model runs, since most of the calculations performed in any model simulation are not saved. A wide range of primary GCM variables should be made available to users, so that they can compute derived variables and statistics to meet their own requirements.

(5) *Identification of critical climate thresholds in physical and ecological systems.* Some physical and ecological systems may have nonlinear responses to climatic variations. This suggests that it may be worthwhile to identify possible climate thresholds to guide scenario development. For example, most crops require minimum levels of cumulative temperature, sunshine, and precipitation before they ripen.

(6) *Improvement of information on atmospheric composition and chemistry.* Some elements of the environment, such as plant growth, are affected by both the climate and the chemical composition of the atmosphere. Inclusion of consistent information on atmospheric composition (e.g., carbon dioxide, aerosols, and ozone) in climate scenarios could help improve the consistency of impact studies.

4. Agriculture

Most forms of agriculture are sensitive to variations in climate. Plants and animals are affected by climatic extremes, such as extended drought, extensive floods, early frost, and severe hail; and the spread of plant pests and diseases can be influenced by quite minor changes in weather. Furthermore, weather can itself govern the timing of many important farming operations.

These effects of weather and climate are closely coupled and have many repercussions both inside and outside of the agricultural sector. In 1976, for example, severe frost in Brazil led to substantial short-term increases in the world market price for coffee, inducing coffee producers in other countries to expand coffee production greatly. Soon after, coffee prices dropped sharply. Similarly, climatically induced shortages of hay and feed grains often cause large numbers of livestock to be slaughtered, with consequent effects on meat, fish, and other prices and on long-term herd sustainability. Delays in planting or harvesting can strongly affect ancillary industries involved in providing agricultural inputs of energy, water, fertilizer, etc., and in food transportation and processing.

Assessing the "net" impact of climate on agriculture is thus a complex task entailing, *inter alia*, consideration of prices, supply/demand relationships, intersectoral interactions, and national and international agricultural policies. Significant progress has been made in recent years in improving our understanding of the first-order effects of climate on agriculture, but only a few attempts have been made to assess downstream effects, human adjustments, and the management and policy context. A brief review of this progress is instructive.

4.1. Recent Progress

Nix (1985) lists five methods of climate impact assessment for agriculture:

(1) *Trial and error*, referring to the repetitive testing against the climatic environment of different activities and treatments and the selection of the best alternative according to the results of the trials.
(2) *Transfer by analogy*, based on the assumption that similar environments will respond similarly to any imposed treatment, so that, for example, vegetation, soil, and water zonations or classifications provide a guide to the agroclimatic potential of different regions.
(3) *Correlation and regressions* (or empirical–statistical modeling), in which one or several climatic variables and/or indices are related statistically to crop measures such as yield.
(4) *Multivariate techniques* that utilize more general statistical techniques than correlation and regression to interrelate several sets of interacting variables simultaneously.
(5) *Systems analysis* (or simulation modeling), in which mathematical models that simplify the mechanisms underlying crop growth are used to simulate crop response to altered environmental conditions.

Prior to 1981, most assessments of the impact of climate on crops were based on empirical–statistical approaches. The emphasis was, therefore, largely on first-order effects, such as changes in average yields. Little consideration was given to likely farm-level adjustments (e.g., in technology), changes in the range of yields and the frequency of occurrence of particular yield levels, and possible spatial shifts of production. In addition, few attempts were made to couple impact models with GCMs, mainly because data from GCM experiments were not available in the form of gridded outputs, but also partly because empirical–statistical models are not always appropriate for estimating the effects of long-term climatic changes. Efforts to assess impact at the global level, such as the 1978 National Defense University study, were extremely primitive and, as Stewart and Glantz (1985) pointed out, potentially misleading.

Recent first-order impact assessments

In recent years, there have been many more assessments of first-order effects of climate on crop growth. Some have continued to rely on regression models, using instrumental climate scenarios as inputs (e.g., Palutikof *et al.*, 1984; Lough *et al.*, 1983; Warrick, 1984). An impact study of agriculture in the European Economic Community (Meinl *et al.*, 1984; Santer, 1985) utilized an empirical–statistical model for winter wheat and a simple simulation model for biomass potential with inputs from two different "doubled CO_2" GCM experiments, one by the UK Meteorological Office and the other by the Goddard Institute for Space Studies (GISS). Rosenzweig (1985) also used the GISS model as the basis for investigating changes in wheat production areas in North America.

Some studies have looked at characteristics other than changes in average yield. For example, as part of a larger study on anthropogenic climatic change (National Academy of Sciences, 1983), Waggoner utilized a simulation model for spring wheat to examine changes in yield *frequencies* for an arbitrary scenario of climatic change (*Figure 4*). Hazell (1984) investigated the spatial and temporal variability of production, yield, and crop areas of major cereal crops in the USA and India. Blasing and Solomon (1984) and Emanuel *et al.* (1985a, b) assessed possible *spatial shifts* in the US Corn Belt and in Holdridge life zones, respectively. Bergthórsson (1985) examined the influence of climatic variations on grasses, livestock, barley, forests, and starvation in Iceland.

Recent integrated impact assessments

Few studies have attempted to assess the downstream implications of first-order crop-yield effects in an integrated fashion. The IIASA/UNEP Climate Impact Project (Parry *et al.*, forthcoming) employed a hierarchy of models to trace downstream effects both within the agricultural sector and in nonagricultural sectors (*Figure 5*). Climate scenarios based on instrumental records and GISS GCM experiments provided inputs into crop–climate models. The resulting estimates of altered average yields or yield probabilities were then input into farm simulation models to estimate effects on farm incomes and other characteristics. Regional economic input–output models were in turn used to evaluate effects elsewhere in the study region (e.g., on machinery and fertilizer purchases and grain storage). Assessments along these lines were conducted in 11 different case study areas where climate is likely to be a major constraint on agriculture. Other elements of the study included:

1. Examination of changes in cultivable area and yield variability.
2. Use of regional analogues to assess the implications of changing cultivars in the case study areas.
3. Incorporation of changes in technology as an initial attempt to evaluate appropriate responses.
4. Coupling of impact models with economic optimization approaches to consider effects on cropped area (e.g., with respect to land allocation in centrally planned economies).

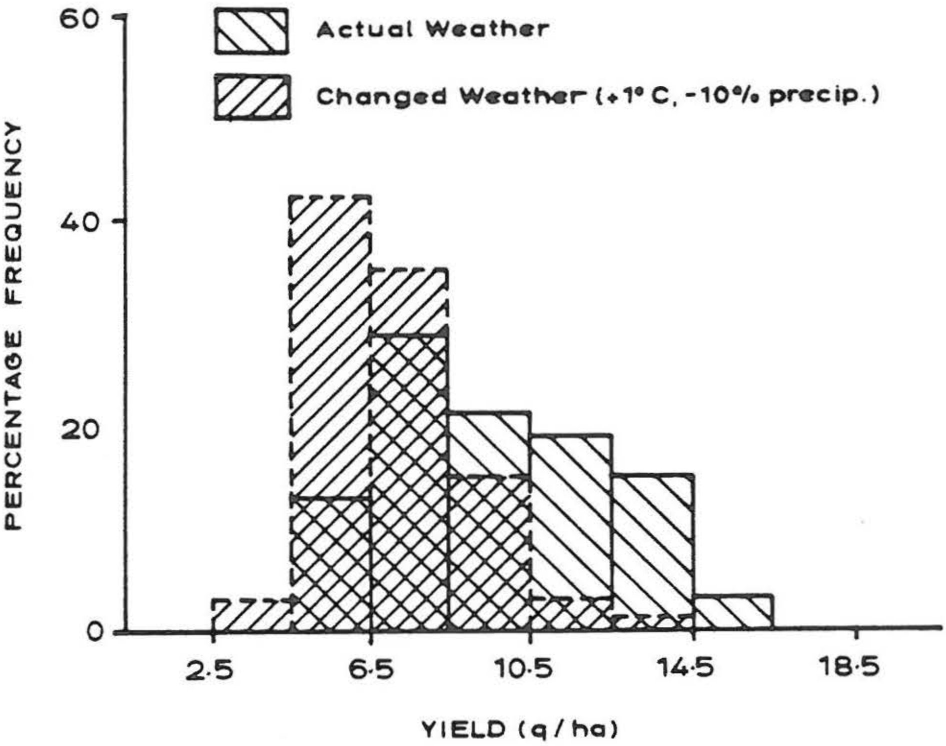


Figure 4. Simulated spring wheat yield for North Dakota, 1949–1980, for actual and "changed" weather. The changed weather case is based on an arbitrary scenario of a 1° C increase in temperature and a 10% decrease in precipitation. Source: Waggoner (1983).

An integrated assessment of a similar kind has been conducted for agriculture in Manitoba and the Prairie Provinces of Canada (Arthur *et al.*, 1986). Designed to be comparable to the Saskatchewan case study of the IIASA/UNEP project, this study utilized two GCM-based climate scenarios (GISS and GFDL) and an historical extreme year (the 1961 drought year). Yield scenarios were derived using crop–climate regression models and input into a linear programming model that used this information to adjust cropping patterns to maximize net crop returns, given physical and economic constraints on the sector. The resulting farm revenues, expenditures, and income were then plugged into an input–output model of the Manitoba economy to estimate effects on other sectors in the region.

Surprisingly little research has focused on the impact of climatic changes on food systems at the global level. Although global models, such as the World Integrated Model (Mesarovic and Pestel, 1974) and MOIRA (Linneman *et al.*, 1979) provide reasonably comprehensive frameworks for exploring global socioeconomic linkages and feedbacks, they do not include climatic variables as explicit inputs (Liverman, 1983; Robinson, 1985). Preliminary experiments with one model indicate that such global models may not respond realistically to sudden climatic perturbations, but may be useful for assessing the impact of slow changes in climate (Liverman, 1983).

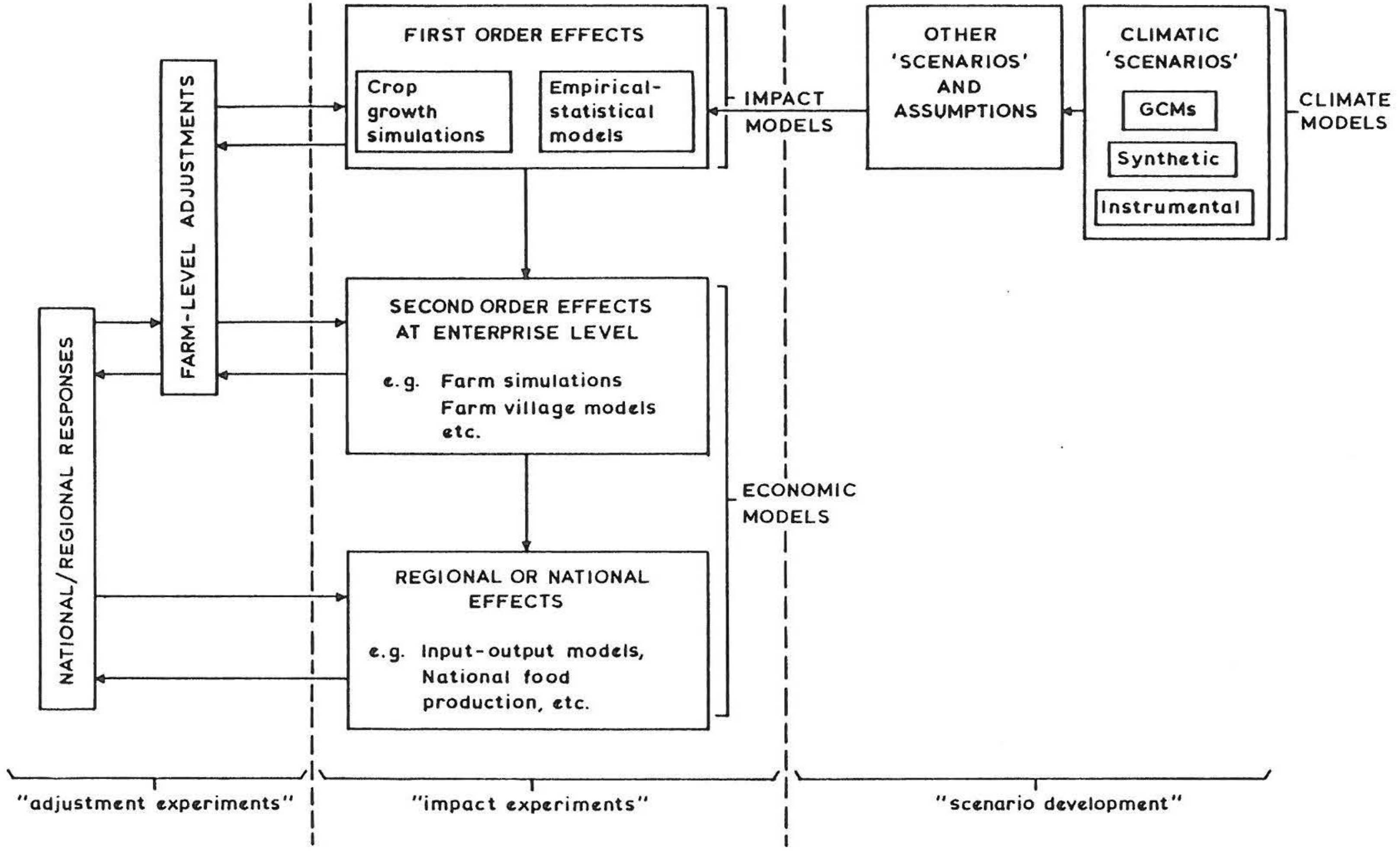


Figure 5. A hierarchy of models for the assessment of climate impact and the evaluation of policy responses in the IIASA/UNEP Climate Impacts Project. Source: Parry *et al.* (forthcoming).

4.2. Promising approaches

The complexity of interactions between climate and agricultural systems suggests that a high degree of sophistication is required to obtain climate impact information useful for policy needs. In particular, crop, livestock, and other biophysical responses to climatic variations need to be closely coupled with economic and social effects at the farm and regional levels. It is vital that assessment methods have the capacity to explore the whole range of possible physical, biological, economic, and social adjustments to climatic variations. Given the many economic and other connections between the individual farmer and global markets, interactive links between analyses at local, regional, and global levels are critical. It is also important to match the spatial and temporal scales of impact assessment to the spatial and temporal scales at which agricultural decision makers and planners operate. Consideration of the range of expected yields and the effects of extremes on agricultural risk is a crucial element of this match.

Recent efforts to integrate agricultural assessments at the regional level (described above) demonstrate considerable promise. Careful linking of biophysical, farm-level, and regional economic models provides a practical method for characterizing key sensitivities, feedbacks, and policy alternatives for the agricultural sector as a whole. Further work on improving model linkages and on developing greater model integration is clearly needed. The approach also needs to be extended to explore effects at a wider range of spatial scales (micro, meso, and macro) and for a broader range of food, feed, and industrial crops. The latter crops may be extremely important for world trade and for generating vital export income in many developing countries. Exploration of short-term effects at the global level should continue, using available global models such as the Basic Linked Model developed by IIASA's Food and Agriculture Program. Careful consideration of interactions with other economic sectors and of changes in agricultural systems is also important (see Section 8).

In addition to these integrated studies, a promising area for study is in the analysis of potential agricultural production. For example, the Agroecological Zone Assessment sponsored by the United Nations Food and Agriculture Organization (FAO, 1984) provides a consistent global assessment of the constraints that the average climate places on agricultural production. Perturbing the climatic data used in these studies would suggest possible shifts in potentially cropped areas and yield changes that might result from climatic variations.

4.3. Recommended activities

A number of specific activities would facilitate efforts to assess the impact of climate on agriculture:

(1) *Identification and improvement of minimum, baseline datasets of key physical, biological, economic, and social variables for multi-sectoral analyses, including efforts to upgrade their spatial and temporal resolution.* Such data

sets should have sufficient resolution to meet the needs of impact assessment at local, regional, and global scales.

(2) *Development of generic models for a much wider range of species and production systems than presently available.* Existing models tend to treat only major grain crops, such as wheat, ignoring other important agricultural resources, such as subsistence, industrial, and export crops; poultry, sheep, cattle, and other livestock; timber and fuelwood; and fisheries. Not only may these resources themselves be sensitive to climatic variations, but they may also strongly interact with other perturbations within agriculture caused by climate.

(3) *Analysis of historical situations to provide insights into cause and effect relationships and the range of available adjustment processes on local and regional scales.* For example, de Vries (1980) has documented the global agricultural impact of the Little Ice Age, Post (1977) the far-reaching consequences of the Krakatoa eruption in the late nineteenth century, and Warrick (1984) the agricultural impact of the 1930's drought in the US Great Plains. However, much more extensive retrospective analysis of climatic effects and human responses is needed, especially for major droughts in, for example, the North American Great Plains, the African Sahel, the South American Pampean Region, and the Northern Plains of China. Work by the International Food Policy Research Institute (IFPRI, 1985) on recent global variability in grain yields furnishes a data base that could be used for studies of the impact of climatic variability

(4) *Investigation of the past and potential future impact of carbon dioxide enrichment, sea level rise, and hydrological changes on agricultural systems.* Environmental changes, such as alterations in atmospheric composition, rises in sea level, and modification of groundwater hydrology, will most certainly accompany future climatic changes. These concurrent changes could have significant impact on major agricultural production systems (e.g., in low-lying deltas) and should, therefore, be explored in conjunction with studies of the impact of climatic changes.

5. Water Resources

The water resources sector may be second only to agriculture in its sensitivity to climatic variations. Shifts in storm tracks, delays in the onset of the monsoon, excessive or deficient snow accumulations, heat waves, cold spells, and other climatic anomalies can have major effects on water resources. Droughts can affect not only the quantity and quality of drinking water, but also the level of hydroelectric power generation, the availability of water in agriculture and industry, the viability of freshwater fisheries, the navigability of rivers, and the quality of recreational and tourism resources. Floods threaten lives, property, environmental quality, and economic well-being. Less dramatic climatic variations can also have significant economic and social effects, both adverse and beneficial.

Present-day water systems – including dams, dikes, reservoirs, sewers, and water treatment plants – already take a high degree of climatic variability into account to protect against extreme events or episodes. However, long-period variations in precipitation, runoff, snowpack, or other climatic factors may significantly decrease margins of safety and threaten the physical and institutional preparedness of the water sector. In particular, given the long lifetimes of existing water systems and the long lead time required for major new projects, the ability of society to respond quickly to climatic change is uncertain.

Hydrologists pioneered the study of the first-order effects of climatic variability on water quantity as an input into designing and managing water facilities. However, they have not in general extended such studies to other aspects of water resource management, including water demand, nor have they attempted to examine indirect effects. Moreover, a prevailing assumption has been that the climate is "stationary", so that possible climatic changes do not need to be considered in planning over the lifetime of present water structures. Only recently have attitudes of this kind begun to change.

5.1. Recent progress

The theory and practice of water-related climate impact assessment is still in a developmental stage. A number of different approaches to estimating the sensitivity of water supplies to climatic variations exist, but their applicability and utility remain controversial (e.g., Beran, 1986). Many case studies of regional water basins have been conducted, but few have used comparable approaches and techniques. Important areas of research, such as the relationship between climate and water quality and between climate and water demand, have received virtually no systematic attention. Few studies have adequately addressed policy needs, e.g., with respect to planning for climatic extremes and possible climatic change, developing alternative water management solutions and institutional arrangements, and providing information on the distribution, timing, and uncertainty of effects.

An active area of research has been the potential water-related impact of global warming due to increasing trace-gas concentrations. Attention has focused particularly on mid-latitude, mid-continental areas, such as the US Great Plains, because GCM experiments with geographic detail suggest that reductions in precipitation and soil moisture may accompany warming in these regions (Manabe *et al.*, 1981; Manabe and Wetherald, 1986). Revelle and Waggoner (1983) estimated the effect of a warmer and slightly drier climate, using an empirical relationship developed by Langbein *et al.* (1949), between mean annual precipitation, temperature, and runoff (see *Table 1*). Recently, Gleick (1986) applied a water-balance model to the Sacramento Valley, using climate scenarios based on outputs from three different GCMs. Cohen (1986) estimated changes in the water balance of the Great Lakes Basin using GISS and GFDL GCM results as inputs into a Thornthwaite-type empirical model (Mather, 1978). One of the serious uncertainties in these analyses is the potential effect of increased atmospheric CO_2 concentrations on plant evapotranspiration (Idso and Brazel, 1984; Wigley and Jones, 1985).

Changes in climate would significantly affect the frequency and severity of extreme conditions, such as droughts and floods. To illustrate, Changnon (1983, 1985) reported that wetter conditions in Illinois since about 1940 have led to fewer droughts, more frequent summer floods, longer winter floods, more storms, and heavier rainfall (*Figure 6*). In the western USA, drought frequencies have fluctuated greatly over the 1914–1980 period, with statistically significant increases in mean annual streamflow in the Pacific Northwest Basin and statistically significant decreases in the Upper Colorado Basin (Meko and Stockton, 1984).

Less dramatic, but no less important, would be changes in total water supplies resulting from possible climatic changes. The Climate Impacts, Perception, and Adjustment Experiment (CLIMPAX) is studying how climatic anomalies over one or tow decades have affected water resources in different areas (Karl and Riebsame, 1984). In Illinois, continuation of ongoing trends toward cooler, wetter, and cloudier conditions could have significant impact on water supplies and therefore on water-using activities such as transportation, agriculture, and manufacturing (Changnon, 1985).

Impact studies focused on specific water regions or basins are likely to be especially useful in meeting policy needs. Regional case studies have ranged from historical analyses (e.g., Dracup, 1977; Howe and Murphy, 1981; Fleagle and Murphy, 1981; Wilhite, 1983) to various empirical and modeling studies (e.g., Němec and Schaake, 1982; Aston, 1984; Cohen, 1986; Gleick, 1986). Examination of the institutional context of water management and the role of climate data has shed light on human adjustments and institutional constraints (Dracup, 1977; Glantz, 1982; Rhodes *et al.*, 1984). Integrated assessment of water and other sectors, such as agriculture, was initiated for western Europe by Meinl *et al.* (1984) and has been proposed for the North American Great Lakes (Timmerman and Grima, 1985; Cohen, 1986).

The impact of climate on water demand is potentially important, but has been given little attention. One example is the Colorado River Basin in 1979, when excessive precipitation in agricultural areas reduced demand for irrigation water releases from the Hoover Dam, thereby leading to a large hydroelectric power deficit. When water was later released to make up this deficit, it caused considerable flood damage in Mexico (Howe and Murphy, 1981). Rapid growth in population and associated water demand could greatly exacerbate drought problems in water basins like that of the Colorado River, where water withdrawals are already high and reservoir capacity is not likely to expand substantially in the next few decades (Diaz *et al.*, 1985).

More detailed reviews of the methods used in water-related impact assessment and of past applications may be found in Klemeš (1985), Nováky *et al.* (1985), and Beran (1986).

Table 1. Comparison of water requirements and supplies for the present climatic state and for a warmer and drier climate in seven western US water regions.[a] The "warmer and drier" case is based on an arbitrary scenario of a 2°C increase in temperature and a 10% reduction in precipitation.[b]

	Present climate						Warmer and drier climate		
Water Region[c]	*Area* ($10^{10}m^2$)	*Mean annual runoff* ($10^{10}m^3yr^{-1}$)	(mm)	*Mean annual supply* ($10^{10}m^3yr^{-1}$)	*Mean annual requirements*[d] ($10^{10}m^3yr^{-1}$)	*Ratio of requirement to supply*	*Mean annual supply* ($10^{10}m^3yr^{-1}$)	*Percent change in supply*	*Ratio of requirement*[e] *to supply*
Missouri	132.4	8.50	64	8.50	3.63	0.43	3.07	-63.9	1.18
Arkansas-White-Red	63.2	9.35	148	9.35	1.67	0.18	4.32	-53.8	0.39
Texas Gulf	44.9	4.92	110	4.92	1.74	0.35	2.47	-49.8	0.70
Rio Grande	35.2	0.74	21	0.74	0.67	0.91	0.18	-75.7	3.72
Upper Colorado	29.6	1.64[f]	55	1.64	1.63[g]	0.99	0.99	-39.6	1.65
Lower Colorado	40.1	0.38	10	1.15[h]	1.37	1.19	0.50[h]	-56.5	2.68
California	42.9	9.56	222	10.18[h]	4.22	0.41	5.71[h]	-43.9	0.74
All 7 regions	388.3	35.09	90.4	35.09[i]	14.93	0.43	16.53[i]	-53.0	0.90

[a] Source: Revelle and Waggoner (1983).

[b] Source: Stockton and Boggess (1979) and calculations in this paper for Upper Colorado Basin.

[c] As defined by the U.S. Water Resources Council (1978).

[d] Projected through year 2000.

[e] Assuming no increase in requirement because of increased evapotranspiration from irrigated farms or reservoirs.

[f] Average "virgin flow" of the Colorado River and Lee Ferry from 1931 to 1976.

[g] Includes allocation to Lower Basin States, California included, of $0.93 \times 10^{10}m^3yr^{-1}$.

[h] Includes water received from Upper Colorado Basin, but not mined groundwater.

[i] Total is less than sum of the column because of flow of Lower Colorado derived from Upper Colorado (*g*).

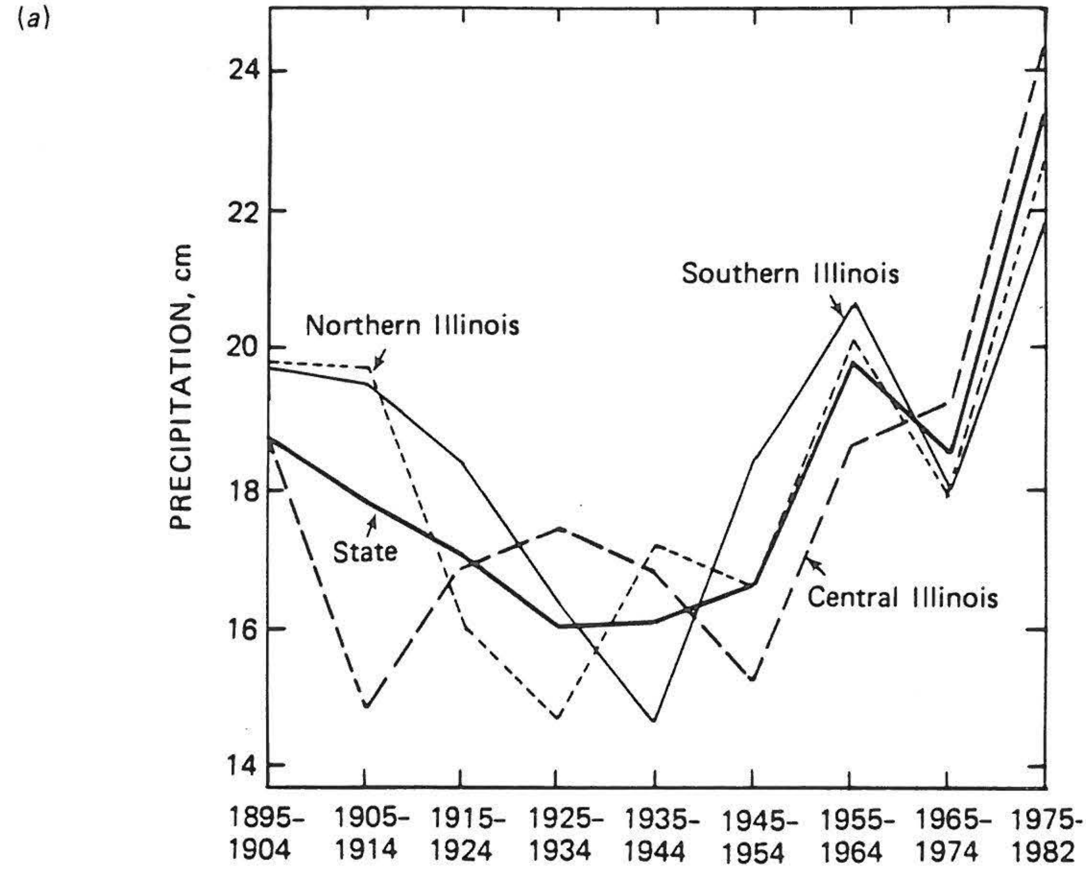


Figure 6. Variations in selected measures of the moisture climate of Illinois since the beginning of the century. Source: Changnon (1983, 1985). (*a*) Mean rainfall by decade (except for last eight-year period) for summer in Illinois and three subdivisions, 1895–1982. Data are for July–August.

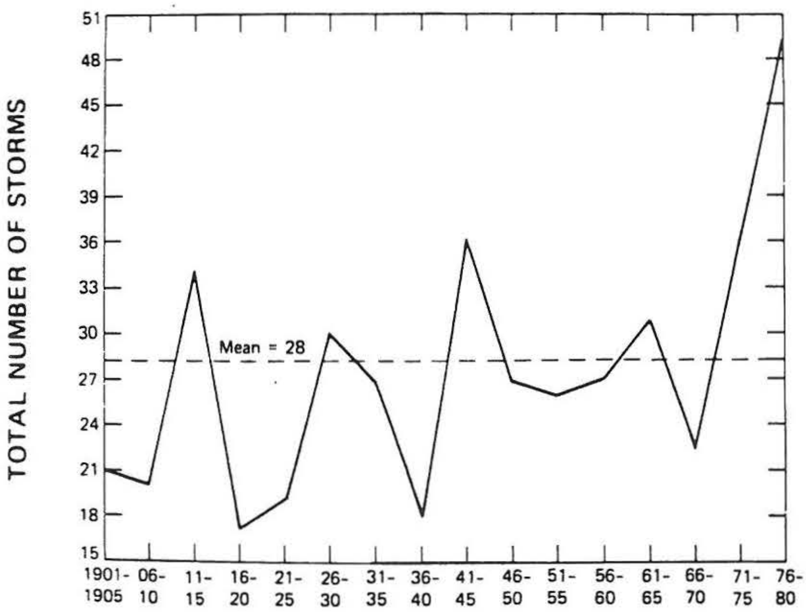
5.2. Promising approaches

In addition to continued work along the lines described above, several relatively neglected issues need particular attention:

(1) *Assessment of the sensitivity of demand for water and water-related services to climatic effects on local and regional scales.* Most of the studies mentioned in the previous section have focused on the impact of climate on water supply. Since water management is as much a matter of meeting multiple water demands, it is useful to know to what degree such demands are sensitive to climatic variability and change. Water demands of interest include irrigation, freshwater fisheries, navigation, waste disposal, cooling, and recreation and tourism. Assessments should consider the short- and long-term alternatives available for these water uses, since these could be an important factor in setting water management priorities.

(2) *Analysis of the physical, ecological, and socioeconomic implications of changes in the frequency and persistence of extreme events such as floods and droughts.* As in other sectors, it may be the extreme events and

(*b*)



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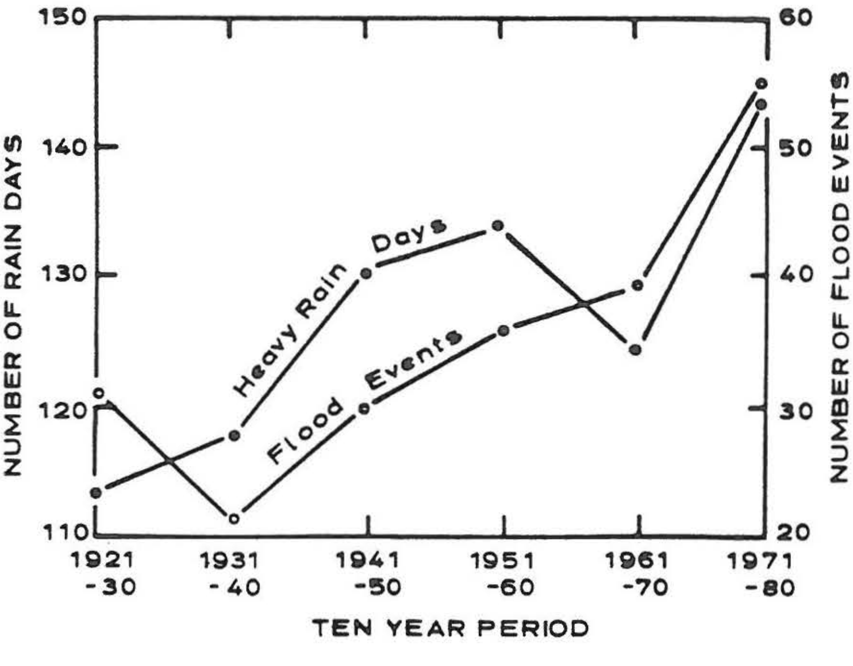

Figure 6. (*cont.*) (*b*) Number of severe winter storms per five-year period in Illinois, 1901–1980. A winter storm is considered severe if it lasts two days and produces glaze over 7,500 km^2 or more than 15 cm of snow. (*c*) Number of heavy rain days and flood events per decade in Illinois, 1921–1980. Rain days are considered heavy if 5.1 cm or more of rain falls during the calendar day. A flood event occurs if the river level rises above the flood crest level defined by the US Geological Survey for one or more days. Flood events are based on data for 10 river basins in Illinois.

episodes, rather than the average situation, that have the greatest effect in both the short and longterm. While a number of studies have examined possible changes in the frequency and persistence of extremes, few have actually assessed the potential impact on the activities and resources that depend on water. For example, there may be thresholds in the frequency of droughts or floods beyond which the economic viability of river transportation, industries, freshwater fisheries, and other activities may be significantly compromised. In Brazil, for example, some companies are now returning to oil-fired generators because the current drought threatens to bring on large-scale rationing of electricity, 95% of which comes from hydroelectric sources (*The Economist*, 23 August 1986: 54).

(3) *Case studies of water quality management in situations of climatic stress.* The quality of water is significantly influenced by climate, both through changes in the degree of dilution (i.e., water quantity) and through changes in pollutant loads stemming from climatic effects on runoff, soil erosion, eutrophication, irrigation demand, navigational dredging, etc. Unfortunately, little is known about these relationships (e.g., between eutrophication and temperature), or about optimal management strategies to control water quality. Case studies focused on water quality management when water quantity is constrained could provide valuable insights. Such case studies should include analysis of the impact of water quality changes on users of water and water-related services (e.g., freshwater fisheries, recreation and tourism, and manufacturing industries).

(4) *Improved links between large-scale climate models and existing regional hydrological models.* To date, very simple methods have been used to link the outputs of GCM experiments with regional hydrological models. Typically, mean changes in temperature and precipitation at a GCM gridpoint are applied to the base data used in the hydrological model. This method is unsatisfactory because of mismatches in spatial and temporal scales in the two different types of models, inconsistencies in their internal hydrologic parameterizations, and the limited degree of interaction possible between the model parameters. New methods are needed to make the linkages more realistic.

5.3. Recommended activities

It is clear that much more research on the impact of climate on water resources is warranted. Although many present-day water systems appear able to cope with climatic variability and some degree of climatic change, there are also many where water supplies already fall short of water demands or where they already exceed existing storage and flood-control capabilities. Examples of the latter situation are the US Great Salt Lake and the North American Great Lakes, where lake levels have risen to record highs and are still rising (Riebsame, 1985). Climatic variability and change could exacerbate such problems or help alleviate them, with consequent implications for short- and long-term management strategies. This suggests that the policy community should encourage impact assessments and be alert to their results.

In light of the long lead times and great cost of major water projects, the vulnerability to climatic variations of those projects currently in progress or being planned should be checked. This is especially important for projects in developing countries or in areas where rapid population growth is expected.

6. Marine Fisheries

The effects of climatic variations on marine fisheries are complex and heterogeneous, varying greatly from species to species and from place to place. Linkages between specific climatic events and fisheries are difficult to substantiate, given large natural fluctuations, extensive human intervention (e.g., fishing, pollution, and habitat destruction), and the extremely limited data available on fish populations. It is, therefore, often difficult to determine even the direction of impact, i.e., whether net fish populations will experience a net increase or decrease, in response to a climatic event. Recent trends toward reduced collection of basic marine data could aggravate this situation.

Nevertheless, since marine fisheries contribute significantly to the food supply and incomes of many nations, this impact of climate is of considerable policy interest. Fishery collapses, such as that of the Peruvian anchoveta fishery in the 1970s, have been attributed, correctly or incorrectly, to climatic events. Spatial shifts in fish populations have created and destroyed fishing industries and brought otherwise friendly nations into armed conflict over fishing rights. Sudden climate-related increases in the productivity of some fish species provide the opportunity for short-term benefits, but also pose the risk of long-term losses if too large and inflexible investments are made.

6.1. Recent progress

Progress in understanding the impact of climate on marine fisheries has been slow, and will probably continue to be slow. Climate affects ocean circulation, surface conditions, upwelling, ice extent and other factors, which in turn affect primary and secondary biological production and thereby marine fish production. *All* of these linkages are poorly understood, although they are in principle comprehensible. Time scales from days to years and decades are involved, and systematic effects due to climate may well be obscured by natural fluctuations. Significant effects in fish communities are likely to occur well before they become evident in commercial fishing, yet few reliable data exist on fish populations; and there continue to be institutional barriers to the effective collection, processing, and dissemination of necessary data. Some short-term assessments of climate-related effects have been made for specific fisheries, but it does not appear that any medium- or long-term studies have been conducted.

Controversy also continues over the degree of influence of environmental versus human factors on fish populations. For example, many reports attributed failure of the Peruvian anchoveta in the early 1970s almost entirely to the 1972–1973 El Niño and to overfishing. However, changes may actually have begun in the summer season of 1969–1970, when anchoveta recruitment began to decline and sardine populations began to bloom. A shift from production dominated by coastal upwelling to production dominated by oceanic processes appears to have occurred. This shift may now be reversing. Paleontological evidence and fishery catch data indicate that periodic shifts of this kind have occurred relatively frequently off the California and South American coasts since about 5,000 BP (de Vries and Pearcy, 1982; Rollins *et al.*, 1986) and around Japan (Kawasaki, 1984).

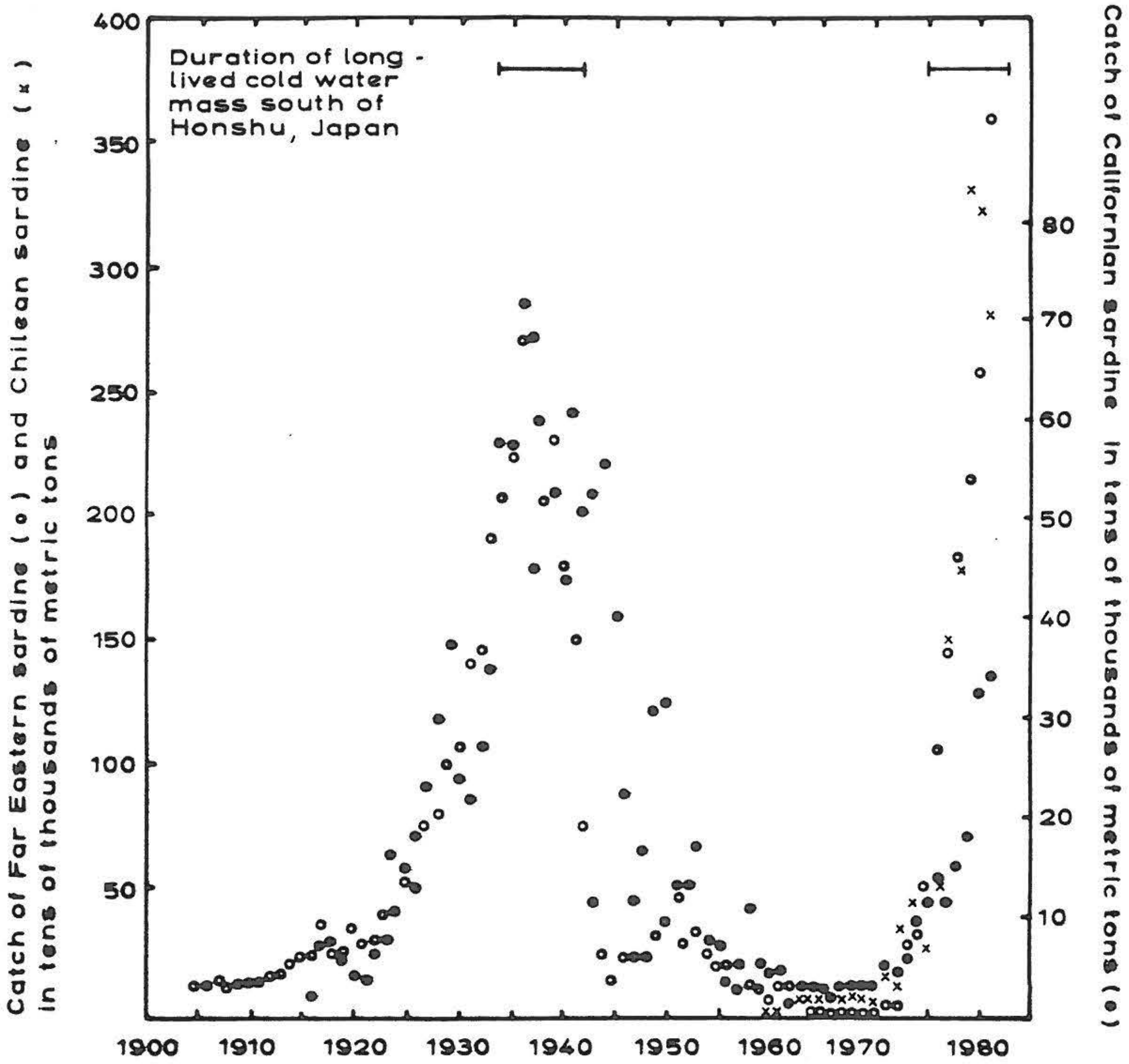

Figure 7. Large-scale variations in the catch of three species of sardine: Far Eastern, Californian, and Chilean. Source: Kawasaki (1985).

Some specific instances of connections between climatic factors and marine productivity have been explored in detail. For example, capelin is a small pelagic fish in the North Atlantic Ocean that burrows into sediments on the ocean floor to spawn. Its recruitment success appears to depend strongly on local coastal temperatures, which are determined by local winds, solar insolation, and ocean currents (Carscadden, 1984). This species is an important diet item for higher trophic levels, so that it provides one mechanism by which both short- and long-term climatic fluctuations may affect commercially valuable species, such as salmon and cod, as well as sea birds and marine mammals. Other examples include recent changes in Ecuadorian shrimp production associated with local climatic Despite these problems, it is clear that environmental fluctuations do contribute to significant variations in some if not all marine fisheries. Most fish species have restricted geographic ranges, more or less clearly bounded by climatic conditions, so that shifts in distribution are at least likely. Large variations in abundance may also occur in some cases. For example, Kawasaki (1985) cites the large-scale, long-term fluctuations of three different, widely spaced sardine species (*Figure 7*) as evidence of a common Pacific-wide ocean variation. Notably, different species may respond differently, so that, for example, sardine populations increased dramatically during the early 1970s at the same time that anchovy populations decreased. Kawasaki distinguishes between species that are stable and predictable in their fluctuations (e.g., tuna and mackerel) and those that are unstable and unpredictable, characterized either by short-term and irregular variations (e.g., the Pacific saury) or by large-scale and cyclical variations (e.g., sardines). These types appear to be closely associated with different ocean habitats and ecological processes. Still other species (e.g., chub mackerel) exhibit both enormous short-term variability and large long-term variations.

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6.2. Promising approaches and activities

In the limnological sciences, there has been considerable success in the development of predictors of fishery productivity in fresh water systems. A useful integrator, the Morphedaphic Index, utilizes environmental variables that can be monitored, such as water temperature, turbidity, flow rates, etc. Unfortunately, due to the open-ended nature of ocean systems, such a direct approach is unlikely to be as successful. However, there have been some recent conceptual developments that should help in the design of studies of the ecological responses of marine fisheries to environmental variability (Bakun *et al.*, 1982; Csirke and Sharp, 1984). Steady and sustained basic research will undoubtedly be required to fill the many gaps in understanding of the interaction between climate and marine fisheries. This falls into the mainstream of much ongoing biological oceanographic research. Nevertheless, there are a number of promising approaches and activities that could yield considerable insight in both the short and long term:

(1) *Empirical assessments based on "zoogeographical correlations", i.e., observed relationships between ocean climates and the spatial boundaries of marine fish populations.* Such empirical studies can shed much light on the mechanisms affecting different fish species and constitute an invaluable data base for developing and testing hypotheses about climate–fishery interactions. They may also be extremely valuable in a policy context, in that they may provide a basis for short-term predictions of fishery shifts and changes.

(2) *Reasonable predictions or scenarios of ocean climate parameters from coupled ocean–atmosphere models.* This is a prerequisite both for empirical and theoretical studies of climate–fishery interactions. Such predictions can help fill out present unknowns in ocean climate conditions and variability and provide inputs into assessments of possible future changes in fishery abundance and distribution. As a starting point, models should provide at least sea surface temperature, salinity, solar insolation, and nutrient levels. This may require the development and use of models that incorporate both physical and biogeochemical processes in an integrated manner.

(3) *Increased and long-term monitoring of marine ecosystems and associated habitats, especially in transitional zones.* Data over several decades or longer are often necessary to characterize fishery variations, detect periodicities, and account for the effects of human activities. Time series of maps of distribution and abundance may also be informative. Monitoring can be expensive, but there is the possibility of acquiring appropriate data in conjunction with existing fishing operations. Use of satellite-based remote sensing, e.g., of net primary productivity in the coastal zone from the Nimbus 7 color scanner, shows considerable promise as way of obtaining long-term marine data over large ocean areas.

(4) *Definitions, classifications, and quantifications of marine species assemblages (communities) and habitats and their sensitivity to climate on regional and global scales.* A fruitful area for study may be possible correlations between quantitative descriptions of species assemblages and quantitative descriptions of habitats. This will require the development and improvement of definitions and taxonomies (e.g., in relation to susceptibility to perturbation). In some areas, elementary research is required to develop baseline zoogeographic descriptions.

6.3. Concluding comment

In the long term, basic research on the mechanisms by which the environment affects fisheries is indispensable. This should include additional research on the early life history of some species in relation to environmental factors. The goal should be to develop credible global and regional assessments of effects in the medium and long term, taking into account both natural and human influences. Effects include both changes in magnitude as well as shifts in fish distributions. Such efforts will usually need to be international, since fisheries rarely respect jurisdictional boundaries.

In the meantime, however, the policy community needs to recognize that *major climatic effects on marine fisheries are highly likely.* Fishery managers should therefore plan for versatility and resilience in their allocation of economic and human resources. Fishing industries should be capable of adapting to rapidly changing fishing conditions and species abundances. Timely monitoring and interpretation of data are of great importance. Increased efforts to encourage flexibility in the species of fish consumed may be needed. Finally, given the difficulty of identifying climatic effects in a timely fashion but their potentially large impact, it may be necessary to take actions before their existence is firmly established, i.e., based on greater levels of uncertainty than scientists normally employ in their scientific studies (e.g., on the basis of 50% rather than 95% confidence limits).

7. Forests and Tropical Biomes

The sensitivity of forests and tropical biomes to climatic variations is of special interest for a variety of reasons. They are habitats for countless plant and animal species; they are unique sources for innumerable raw materials and useful products; they are essential links in the biogeochemical cycling of carbon and other basic elements; and they play important roles in the climate at local, regional, and global scales. Unfortunately, increasing human pressures on these valuable resources may interact with climatic effects to accelerate ecosystem degradation and retreat.

The principal climatic constraints on forests and tropical vegetation are temperature and moisture, but other climate-related factors such as fire frequency, sea level, and pest and disease prevalence may also be important. In the Northern Hemisphere, northern parts of the boreal-temperate biome tend to be limited by low temperature. Further south, moisture is often the key limiting factor. In general, tree species are well adapted to their present climates, and their distributions are more- or- less in equilibrium with prevailing climatic conditions.

The time scale for climate-induced changes in forests and tropical biomes is likely to be generally comparable to the time scale of natural forest rotation and land-use changes, i.e., 50 years or more. This suggests that the initial focus for policy-oriented research should be on shifts in the boundaries between ecosystems – for example, between boreal forests and tundra and between tropical forests and savannas – and their long-term implications. Consideration of shorter time scales (i.e., years to decades) may be necessary with respect to the occurrence of catastrophic events, interactions with other environmental factors such as air pollution and acid rain, the spread of fast-growing species, and increased human pressures for land and biomass. Some effects, such as changes in fire frequency, increased oxidation of peatlands, and acceleration of deforestation due to climate-induced population migration, could have important feedbacks for atmospheric carbon dioxide levels.

7.1. Recent progress

The impact of climate on forests and tropical biomes has received relatively little attention to date. For example, neither biome was treated in the SCOPE volume on climate impact assessment (Kates *et al.*, 1985). While some qualitative information is available, few attempts to quantify climatic effects have been made. A qualitative summary of the possible sensitivity of different tropical ecosystems at different time scales is given in *Table 2*.

Both *static* and *dynamic* approaches can be used to quantify the impact of climate on biomes. Static approaches assume that close relationships exist between the biota and the climate (and soils). Shifts in climatic conditions should, therefore, lead eventually to shifts in biomes. This approach was used by Emanuel *et al.* (1985a, b), who applied the Holdridge Life-Zone Classification System first to data for the present climate and then to data for a modified climate. In the latter case, temperatures were altered by amounts derived from an increased-CO_2 experiment with the GFDL GCM (Manabe and Stouffer, 1980). Precipitation was held constant. Comparison of the resulting world vegetation maps suggests that significant shifts and changes in the areal extent of biomes could occur, including substantial reduction in the area of boreal forest (*Figure 8*). Similarly, Kauppi and Posch (forthcoming) developed a regression relationship between climate and the potential for plant primary production in the boreal zone and applied it to output of a GISS GCM experiment. Their estimate of the zonal shift in the boreal zone in a warmer climate is smaller than that obtained by Emanuel *et al.* (1985b), but is still significant. Other examples of the use of simple regression relationships include Solomon *et al.* (1984), Bergthórsson (1985), and Kauppi and Posch (1985).

Dynamic approaches attempt to take into account factors affecting the time-dependent response of biota to changing conditions, including migration rates, possible lag effects, genotype development, and species competition. Shugart *et al.* (1986) reviewed the available forest simulation models and concluded that they could be used to predict some of the heterogeneity of response at the regional and continental scale. Solomon *et al.* (1984) applied a forest-stand simulation model to 21 locations in eastern North America under a time-dependent scenario of CO_2-induced climate warming. Human activities and responses, especially in managed ecosystems, may also be crucial. A preliminary effort to look at the response of the forest sector to climate-induced change was carried out by Binkley (forthcoming).

Table 2. Qualitative sensitivity of tropical biomes to climate variations.[a]

	Sensitivity to Climate Variations			
Biome	*Several years*	*100–1000 years*	*Long-term trends*	*Level of Awareness*
Tropical rain forest				
< 2500 mm[b], 2-3 dry months	medium high	high	very high	Generally low awareness; other problems, such as deforestation and conversion, take precedence
> 2500 mm[b], 0-1 dry months	low	medium	medium high	
monsoon	low	medium	high	Special case: hydroelectric watersheds
Deciduous forests and savannahs				
semi-arid	very high	very high	very high	Attention given mostly to desertification, loss of pasturelands, etc.
seasonal	low	low	medium high	
Mangrove	very low	medium	very high	Low awareness
Coastal areas, estuaries, etc.	low	medium	very high	Awareness potentially high because of cities, high productivity lagoons, etc.
Mountains	low	low	low	Shift in land use patterns
Islands	low	medium	medium	Depends on topography; hurricane frequency important

[a] Source: Herrera (1986).

[b] Mean annual precipitation in millimeters.

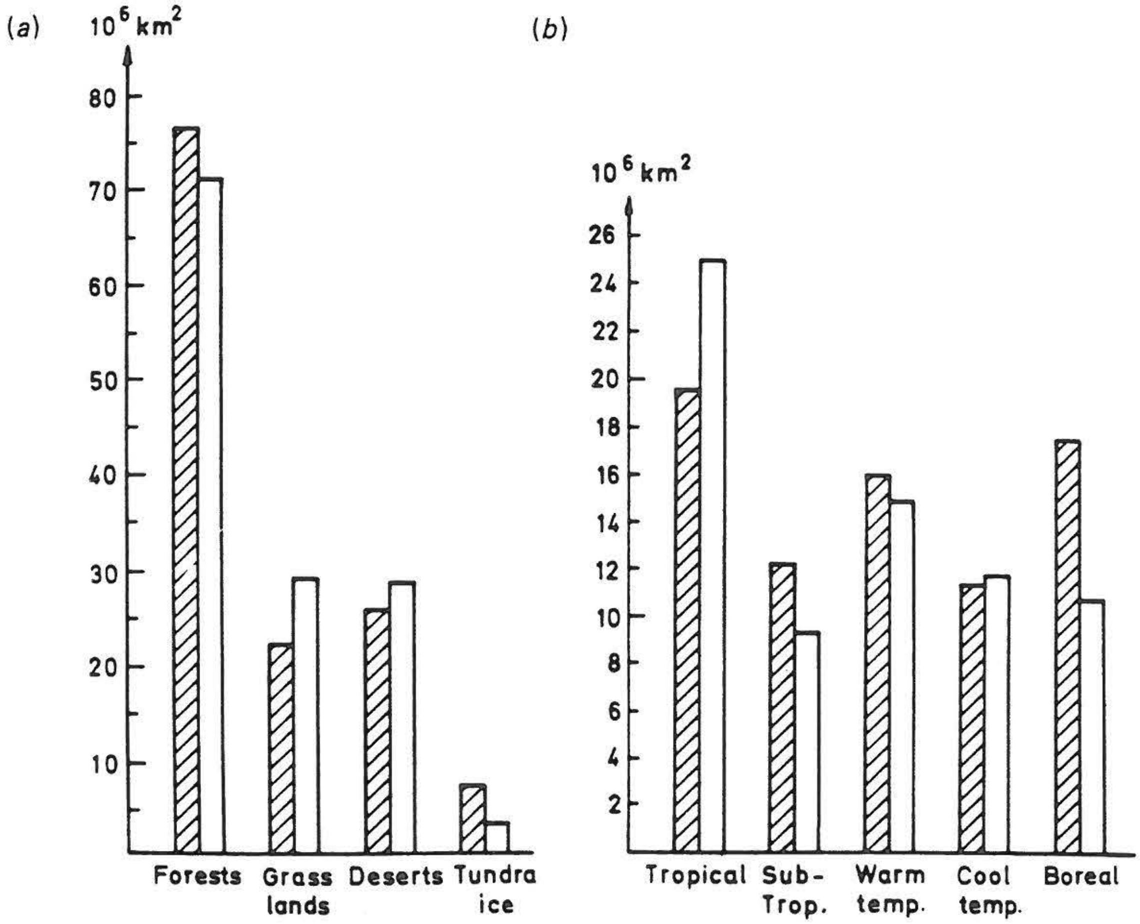

Figure 8. Estimated changes in areal extent of (*a*) major forest types and (*b*) biomes under doubled CO_2 levels. Source: Emanuel *et al.* (1985b).

7.2. Promising approaches and activities

Given the low level of awareness that appears prevalent regarding the potential impact of climatic variations on forests and tropical biomes, efforts are needed primarily to identify the principal sensitivities to climate, characterize their magnitude, and expand the basic data base for further research and assessments. Promising approaches and activities for carrying out these tasks include:

(1) *Analysis of shifts in ecosystem boundaries (e.g., tree lines and limits of vegetation zones) as a function of changes in climatic parameters.* The quantitative assessment of biome shifts described above permits estimation of at least the potential first-order impact of climate on ecosystems. Further development of these approaches and their application to different ecosystems could improve understanding of sensitivity to climate of both managed and unmanaged ecosystems. Possible improvements include use of more sophisticated climate scenarios, consideration of soil and moisture constraints, and assessment of the mix of species in transition zones.

(2) *In situ studies, baseline studies, and model development as the basis for satellite-based remote sensing of changes in ecosystems, forest cover, fire frequency, erosion, and sedimentation.* Recent advances in satellite-based remote sensing techniques now make possible the routine acquisition and analysis of detailed data on spatial and temporal changes in surface vegetation and other conditions. Such techniques are particularly valuable in providing data for areas of the world where ground data are sparse or unreliable. Space-based monitoring can be used to examine normal seasonal development of vegetation and detect unusual events, anomalous episodes, and trends. It may also be useful for providing early warning, identifying especially fragile or robust areas, and suggesting and testing hypotheses. However, adequate interpretation of these data require the coordinated provision of consistent and reliable *in situ* data, baseline data, and calibration models. A possible framework for this type of effort has been suggested as part of the proposed International Geosphere–Biosphere Program (National Academy of Sciences, 1986).

(3) *Examination of the potential effects of changes in fire and storm frequency in both managed and unmanaged forests.* Changes in climate or its variability could entail changes in the frequency of storms, droughts, and other extremes, with significant effects on boreal, temperate, and tropical forests. A particular concern is the possibility that warmer and possibly drier conditions in some regions and seasons could lead to increasing fire frequency. Fires could be particularly disruptive to ecosystems as well as to human activities. There could also be important regional or even global climatic feedback through the variation of atmospheric particulate loadings and carbon dioxide releases.

(4) *Study of the effects of changes in sea level and sedimentation rates on mangrove swamps and other coastal ecosystems.* Mean sea levels have increased 0.1 to 0.15 m during the past century and could increase 0.5 to 2.0 m by the end of the next century if the climate warms significantly as the result of increasing trace gases (World Climate Program, 1985). Such increases could have substantial impact on mangrove swamps and other coastal ecosystems, especially if human interventions prevent their landward migration. An important uncertainty is whether sedimentation rates in these ecosystems can compensate for accelerated rates of sea level rise by raising land levels (Delft Hydraulics Laboratory, 1986).

(5) *Detailed study and long-term monitoring of the northern timberline.* Climate models suggest that climatic warming due to increasing trace gases would be amplified at high latitudes. Since northern high-latitude boreal forests are limited primarily by temperature, they may be a useful indicator of developing climatic change. The northern timberline is a visible boundary that can be monitored both in the field and by satellite. Timberline forests have remained generally unmanaged and unpolluted and are therefore free from influences that could obscure the effects of climatic variations. They

thus constitute a unique "laboratory" for studying and monitoring the impact of climate on the biosphere on a hemispheric scale.

8. Integrated Regional Assessment

Environmental and socioeconomic systems are closely interrelated at local and regional levels. They are likely to be simultaneously sensitive to climatic variations in diverse ways. Although it is traditional and convenient to consider these sensitivities in the context of individual socioeconomic sectors (as in the previous sections of this Research Report), in actuality, climatic variations, such as drought, have far-reaching effects that cross sectoral boundaries. Similarly, many policy alternatives for dealing with climatic effects have multi-sectoral implications. This is often the case, for example, in managed river systems where droughts and floods can cause widespread problems for diverse water users and where decisions about inadequate or excessive water supplies typically involve major tradeoffs among users (e.g., Howe and Murphy, 1981; Fleagle and Murphy, 1981).

An *integrated* approach to the assessment of the impact of climate is therefore crucial to the development of *comprehensive* response strategies. A *regional* approach makes sense because a high degree of climatic homogeneity and close sectoral interconnections are often found at the regional level (e.g., in water basins). An *integrated regional assessment* approach should include examination of:

(1) *Points of vulnerability*, or climate-sensitive features, in regional socioeconomic systems;
(2) *Salient linkages*, or key feedbacks, between socioeconomic sectors.
(3) *Distributional characteristics* of regional effects and policy alternatives.
(4) *Overall context* of climatic variability and change in the regional socioeconomic system.

In practice, an integrated regional assessment could include several parallel studies with specified linkages. Some tradeoffs between sectoral detail and intersectoral linkages might be necessary. Careful definition of objectives and priorities would be needed to ensure that pertinent components and linkages are taken into account in the analysis. Assessments should incorporate the perspectives and understanding of those with direct policy experience in the study region.

The importance of understanding distributional characteristics and the overall context is illustrated by the experience of Brazil. As recently as 1979 and 1980, recurrent drought in Brazil's northeast region had severe impact on the rural population despite several decades of intensive governmental effort to develop water resources, improve infrastructure, and establish industry. Although most measures appeared sensible on their own, they lacked coordination, continuity, and a complete view of the problems induced by drought. In particular, these measures failed to address the underlying reason for the rural population's vulnerability to drought – namely, their poverty. A new effort, the

Northeast Project (Projecto Nordeste), now incorporates an integrated regional policy designed to increase the resilience of the population to drought by improving income and land distribution, eliminating poverty, and strengthening the economy.

8.1. Recent Progress

Unfortunately, experience with integrated regional assessments is at present very limited, and the methods available are primitive. As noted in section 4.1., some attempts have been made to link the agricultural sector with the general economy using regional input–output models (Parry *et al.*, forthcoming; Arthur *et al.*, 1986). However, no other sectors were treated in detail and no explicit two-way feedbacks with other sectors were included. Studies by Lough *et al.* (1983) and Meinl *et al.* (1984) examined several sectors simultaneously, but did not treat downstream or interactive effects in depth. Palutikof (1983) demonstrated the net effects of both seasonal climatic extremes and normal climatic variations on industrial production in Great Britain over the period 1958–1979 using multiple regression techniques, but did not trace these through the regional economy in detail. Cohen (1986) has proposed an integrative framework for linking climatic variations, water-related effects, and the regional economy of the Great Lakes (*Figure 9*), but examined only the direct impact of selected climate scenarios on the net water supply in the basin.

Studies of historical situations constitute another body of relevant work, although their primary focus has also tended to be on agriculture. These often illustrate the types of interactions and the elements of the societal context that may significantly affect the overall impact of climate (e.g., Post, 1977; de Vries, 1980). Wigley *et al.* (1985) provide a list of major historical climate impact assessments.

A different approach has been taken by the IIASA study on Future Environments for the European Continent. One of the objectives of this study is to characterize the large-scale environmental transformation that could be associated with plausible scenarios of European socioeconomic development over the next century. Possible future climatic variations and impact are only one component considered in the study.

8.2. Promising approaches

Much further development of concepts and methods is clearly needed to ensure a reasonable degree of realism in integrated assessment efforts. Topics that show special promise include:

(1) *Identification of the salient sensitivities of and interactions between components of regional systems under various scenarios of climatic variation.* A systematic way to approach this would be to (*a*) trace the sequential impact of climatic variations (based on climate scenarios) in each sector, holding other sectors constant (*ceteris paribus*); (*b*) analyze several sectors

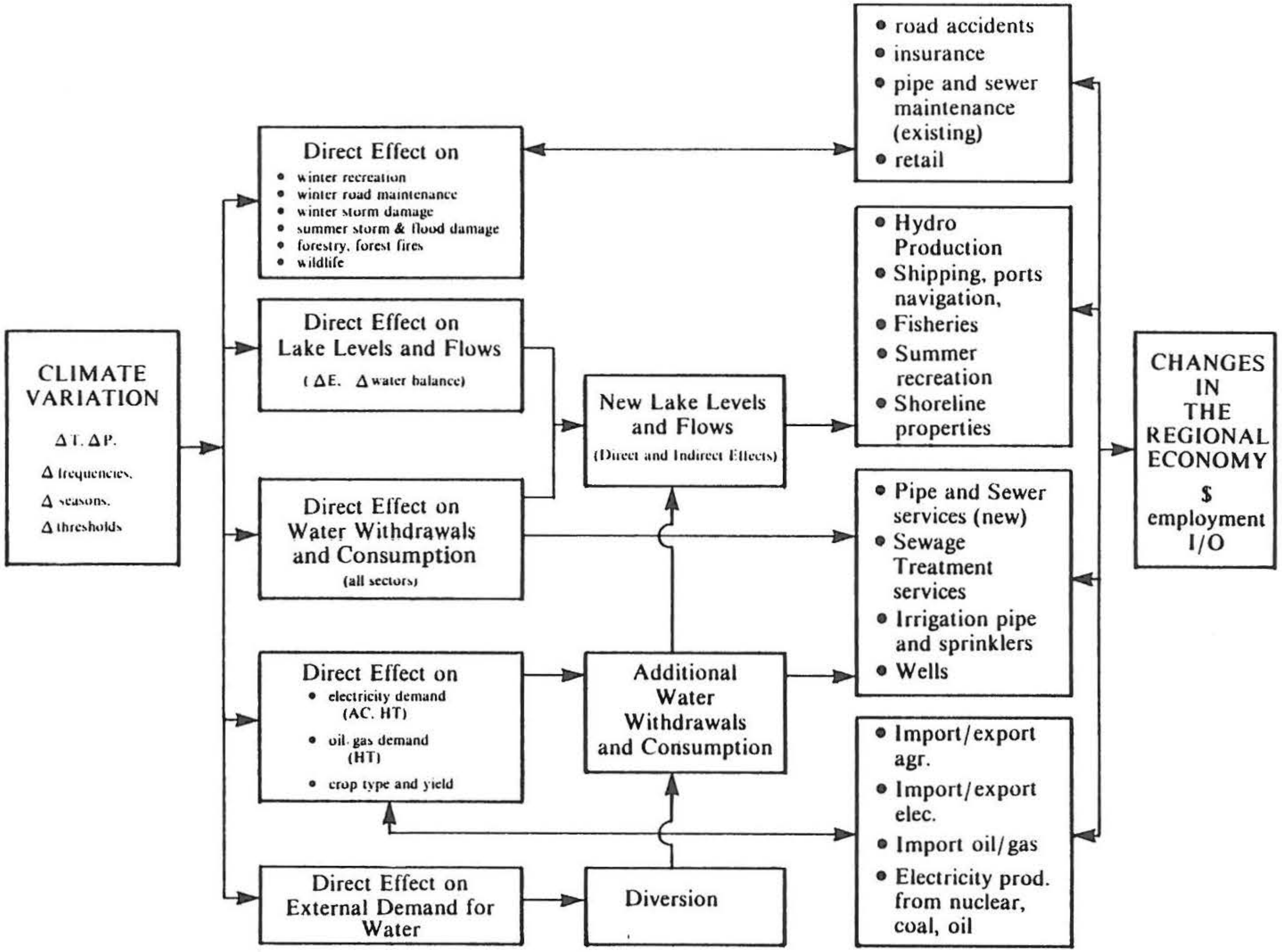

Figure 9. A proposed integrative framework for assessing the water-related impact of climatic variations in the Great Lakes regional economy. Δ = change, T = temperature, P = precipitation, E = evaporation, AC = air conditioning, HT = space heating, and I/O = inputs/outputs. Source: Cohen (1986).

at once to identify feedbacks and incompatibilities; (*c*) relax the *ceteris paribus* assumptions to examine possible technological, economic, and social adjustments; and (*d*) compare several different regions.

(2) *Examination of the compatibility of analytical models used in individual sectors, such as agriculture, water resources, forestry, and energy consumption, and of methods for linking such models.* The models currently available for different sectors and for different activities within sectors may well have differing conceptual bases, numerous conflicting assumptions, widely varying spatial and temporal scales, subtle differences in definitions, common variables with different values, and other incompatibilities. These require careful review and adjustment to ensure that reasonably unbiased, error-free, and, it is hoped, realistic links are made between models.

(3) *Analysis of the distributional characteristics of impact within regions and their implications for regional-scale institutions and policies.* The distribution of impact in space, across income groups, between generations, or along other dimensions is likely to be a critical element in the ability of societies to respond to climatic variations. One subregion or population group may be more severely impacted than another owing to the uneven effects of climate (e.g., a sea level rise or agricultural drought), differences in vulnerability (e.g., poorer housing quality or health status), or both. Even if some subgroups would eventually benefit from a climatic change, disruption costs may be large and unevenly distributed. Within a socioeconomic region, there are typically institutional mechanisms and pressures to assist those more severely impacted, thereby distributing the impact to some degree across the region as a whole. Similarly, actions taken at the regional level to alleviate the impact of climate, such as the construction of water facilities, often entail displacement of large numbers of people, uneven losses of property, and/or heterogeneous risks. A common consequence is that many measures are subject to lengthy delay, substantial alteration, or even cancellation.

(4) *Exploration of the joint effects of climatic variations, demographic, environmental, and technological changes, and adjustment strategies.* Future variations in climate will affect not the world that exists today, but one significantly modified by population growth, environmental change, technological developments, institutional evolution, and other changes. While it is probably not possible to predict most of these changes with any certainty, exploration of how future climatic variations might interact with future conditions at the regional level may be extremely instructive. Such exploration could, for example, suggest relatively inexpensive actions now that could greatly ease future problems, such as reserving undeveloped land for future water facilities, designing new infrastructure with possible climatic variations in mind, and instituting zoning restrictions on lakeside development.

8.3. Additional considerations

Regional studies were proposed for North and South America, Europe, the Arctic, India, and Africa at the 1985 Villach Conference (World Climate Program, 1985). *It is important that these regional studies adopt an integrated assessment approach*, such as that outlined here. Pilot studies should be carried out in both developed and developing regions and in regions where climatic variations are an especially significant and pervasive factor in human activities and welfare. Both climatic variability and possible climatic changes should be considered. As much as possible, studies should be designed in parallel to permit comparisons between regions. Active interaction with those with direct policy experience in each region is vital. The results of integrated regional assessments should be extremely useful inputs into policy studies at the regional and global level.

9. Policy Issues

The impact of climate on natural and human resources is clearly of major policy interest in its own right in both the short and long term. Present-day climatic variations exact large human and social penalties in most developing countries and many developed ones. Possible future climatic changes due to increasing atmospheric trace gases, decreasing stratospheric ozone, or other factors could significantly increase these penalties. But as discussed in the previous chapters, policy-oriented assessments of the impact within individual sectors and across socioeconomic regions provide an opportunity to reduce many of these penalties and increase benefits from climatic resources by providing timely and creative guidance at local, regional, national, and international levels.

Of comparable importance is the impact of climate on many pressing, present-day policy issues. In developing countries, droughts, floods, and other climatic extremes can upset development plans, drain foreign currency reserves, accelerate desertification and deforestation, worsen migration problems, and contribute to political instability. In developed countries, climatic variations can exacerbate existing problems of international migration, transboundary pollution, trade imbalances, soil erosion, and resource depletion.

These close links with other policy problems underscore the need for integrated impact assessment and response strategies at national and international levels. Assessment studies need to address the full spectrum of climate variations, impacts and responses, and their interaction with society. Tendencies to focus on narrow aspects of the broad climate problem may be counterproductive in the long run. Developing integrated assessment approaches is certainly a challenging task, but it is also a necessary one.

9.1. Recommended activities

Translating assessment into policy and action, however, clearly requires more than just scientific research. It is also necessary to convey the results of assessment studies to the policy community and the public and to provide continuing advice and guidance on alternatives and their implications. This suggests a number of useful activities on the part of the scientific community:

(1) *Analysis of the future evolution of anthropogenic perturbations to the climate and the biosphere and exploration of the feasibility of strategies to control or delay them.* One major policy option about which there is still considerable uncertainty is whether it is feasible or practical to control anthropogenic emissions of trace gases and other perturbations sufficiently to reduce and/or delay future anthropogenic climatic changes. It may also be important to reduce or delay other perturbations to the biosphere, since these may interact synergistically with climatic changes. The timing and rapidity of future changes may be critical factors in the ability of society to adapt and are therefore important inputs into impact assessment studies.

(2) *Identification of possible thresholds in impact and responses that might be associated with nonlinear or stepwise climate sensitivities.* Many environmental, economic, and social systems are capable of accommodating limited variations in climate. In developed countries, reservoirs, dikes, food and energy reserves, disaster relief services, and other mechanisms exist that can ameliorate the most severe effects of short-term climate extremes. In developing countries, fewer governmentally organized options may exist, but there may still be considerable resilience based on kinship networks, population mobility, and traditional survival methods. However, in all cases, there are likely to be thresholds beyond which existing mechanisms become increasingly inadequate or increasingly susceptible to catastrophic failure. Identification of such thresholds based on past experience or on other techniques would enable more precise measurement of the importance of climate sensitivities identified in sectoral and regional impact assessments.

(3) *Exploration of methods to present scientific information on the impact of climate in a way that conveys the unavoidable uncertainties involved, yet preserves both the urgency of the issue and the credibility of the scientific community.* The assessment of the impact of climate on society entails many uncertainties. Questions of credibility unavoidably arise. Scientists and scientific policy advisors should recognize that their credibility primarily depends on their provision of the best scientific advice available. Credibility problems should be lessened if advice can be based on a widespread consensus of scientific experts. An unwillingness to provide advice because of its uncertain scientific basis may be interpreted as a judgment that no action is required. Scientists may also lose credibility in the

policy community if their only advice is that further research is necessary, especially if there are public demands for action. It is thus important for the scientific community to strive to improve methods for conveying climate impact information that explicitly deal with – but do not overemphasize – the uncertainties.

In this context, it is important to recognize that decision makers are generally willing to accept uncertainties and controversies and, indeed, are usually accustomed to dealing with them. They are often interested as much in the plausible, "not impossible" scenarios as in the "most likely" scenarios. Scientists should convey their best judgments on possible outcomes in terms that are unambiguous, yet honest with respect to the level of uncertainty. They should refrain from sensationalism, yet communicate in clear, jargon-free language understandable to the public, the media, and decision makers.

(4) *Development of methods to assess the full sociopolitical implications of impact and responses, and their interactions with other policy issues at regional and global scales.* It is apparent that existing methods for social and political impact assessment may be limited in their ability to deal with the impact of climate in its broad policy context. This broad context includes the implications of any measures to cope with climatic variations on other aspects of the environment, e.g., reductions in fossil fuel use leading to lessened climatic change and acid deposition. New and innovative methods need to be explored. One approach is the use of "policy exercises" recently proposed by Clark (1985).

(5) *Establishment of an international framework for assessing the risks and benefits of climatic changes and the effectiveness of alternative policy actions.* From a policy perspective, a difficult task will be the development of an international consensus on the risks and benefits of climatic changes and on effective multinational policy actions. The scientific community can play an important and constructive role in the development of such a consensus by establishing at an early date an international framework for assessing these risks and benefits and for evaluating the advantages and disadvantages of various management strategies. It will be particularly important to include within this framework detailed consideration of the full range of possible climatic effects, including social and political implications. However, considerable care will be necessary to ensure that this international framework remains objective, open-minded, and independent of short-term political considerations. This suggests that the international framework should be established under the auspices of a program such as the World Climate Program, which has both governmental and nongovernmental sponsorship and involvement.

9.2. Concluding comment

In these and other activities, increased and continuing interaction is needed among a wide range of participants from both market-oriented and centrally planned economies, developed and less developed countries, and the scientific and policy communities. This interaction will be critical to building a common human interest in the improved worldwide management of the impact of climatic variations.

10. Epilogue: Communication across the Science–Policy Gap

The evidence of this report, and the meeting upon which it is based, suggest that there are many pressing needs for information yet to be met, and many promising avenues of research yet to be explored. Developing a practical union between such needs and such research is likely to be a lengthy and difficult process, to which this effort is only a small contribution. Nevertheless, the dialogue begun here is valuable not only because of the specific recommendations it has generated, but also because it has demonstrated the value – and necessity – of increased interdisciplinary communication between the scientific and policy communities.

To be sure, this communication is at present more disciplinary than interdisciplinary. Scientists have difficulties in looking beyond the simplifications and uncertainties inherent in their analytic methods; policy makers have difficulties in looking beyond the latest crisis or the most recent scientific pronouncement. Misunderstandings can arise from the apparently conflicting priorities of scientists who, in the long run, seek basic understanding of natural and human systems and policy makers who, in the short term, seek practical guidance on pressing natural and human problems.

What is now becoming clearer, however, is that these different objectives need not conflict, and that scientists and policy makers share many of the same objectives. Many, if not most, scientists involved in climate impact assessment are deeply concerned about the diverse climatic threats we now face, including the devastation of drought in the developing world and the possibilities of a drastically warmer or cooler world. Their research, even if somewhat esoteric on the surface, is in many cases of immediate practical value, as well as of long-term scientific worth. Much of the historical work cited in previous sections of this Report (e.g., on human and institutional responses to drought, flood, and other natural hazards) is of this nature.

By the same token, many, if not most, of those in the policy community involved in climate impact assessment are interested not only in short-term measures, but also in long-term solutions to ongoing and potential problems posed by climate. They support basic research on the interactions between climate and society, and often strongly encourage research in areas that have received little attention to date. This is the case, for example, regarding the interaction between climate and other pressing policy problems, such as international migration and economic development, discussed in section 9.

Further dialogue between the two communities is certainly needed to clarify areas of common concern and to develop priorities among various research avenues. This is not a task that can be accomplished by a small group of people in a single meeting. Dialogue is needed both at the working level for specific topics (e.g., for a particular economic sector or region) and at the integrative level (e.g., for assessing the risks and benefits of potential climate change). Many specific recommendations along these lines have been made in this Report.

Nevertheless, some common themes and high priorities are already evident. One is the need for climate scenarios to provide reasonably realistic, even if hypothetical, indicators of the nature, magnitude, and distribution of climatic variations. Such scenarios are of broad utility in diverse approaches to climate impact assessment in many different subject areas.

Another common theme is the importance of careful links between often disparate models. It is frequently convenient, if not a practical necessity, to utilize existing models of natural or human systems developed within different scientific disciplines. The complexity of interactions between natural and human systems then makes it imperative to develop suitable links between such models, despite often widely varying spatial and temporal scales and varied assumptions and simplifications.

Given the limitations of formal modeling methods in many areas of climate impact assessment, analysis of historical situations appears to be a useful technique. Such efforts provide an opportunity to check the realism of models against past experience and assess the limits of their applicability. Furthermore, they can help elucidate the strengths and weaknesses of different policy alternatives under realistic conditions.

Scientists are beginning to recognize the importance of looking at a more complete set of climate impact parameters and their statistical properties. In a variety of situations, the magnitude and frequency of extremes, the variability of a parameter in space and time, the distribution of effects across population groups, and other such nontraditional characteristics are of demonstrable significance. This supports the hypotheses, delineated in section 2, regarding the need to assess the range of possibilities and possible policy responses, especially if there may be nonlinear or threshold responses to climatic perturbations.

Unfortunately, data are too often a key limiting factor in studies of the impact of climate. Environmental, economic, and social data are frequently scarcest where the effects of climate on environmental, economic, and social systems are most intense. Consistent long-term monitoring, although in general expensive and difficult no matter what the discipline, is a necessity. So, too, are efforts to reconstruct past data from historical proxy sources and to develop new sources and types of data (e.g., from satellites).

Finally, a striking theme to emerge from interdisciplinary dialogue is the diversity of promising research approaches. Many of these approaches have already yielded concrete policy information of considerable utility and value. In many instances, methods developed in one subject area are readily transferable to other areas. For example, the strategy of examining marginal areas using climate scenarios and linked models, successfully applied by Parry *et al.* (forthcoming) to the agricultural sector, is likely to be of considerable utility in the water sector.

These common themes suggest that the field of climate impact assessment, though nascent as pointed out at the beginning of this Report, is developing rapidly and creatively. It is hoped that the interdisciplinary dialogue presented here will help foster further creativity and suggest ways in which the field can reach its full potential to meet policy needs.

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Marine Fisheries Regional

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Water Resources

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Appendix C: Acronyms and Abbreviations

BP	Before Present
CLIMPAX	Climate Impacts, Perception, and Adjustment Experiment
cm	centimeters
CO_2	carbon dioxide
°C	degree Celsius
FAO	Food and Agriculture Organization, United Nations
GCM	general circulation model
GDFL	Geophysical Fluid Dynamics Laboratory, Princeton University
GISS	Goddard Institute for Space Studies, US National Aeronautics and Space Administration
ha	hectare
ICSU	International Council of Scientific Unions
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
m	meter
mm	millimeter
MOIRA	Model of International Relations in Agriculture
q	quintal (100 kilograms)
SCOPE	Scientific Committee on Problems of the Environment
UNEP	United Nations Environment Program
WCIP	World Climate Impact Study Program
WCP	World Climate Program
WMO	World Meteorological Organization
yr	year