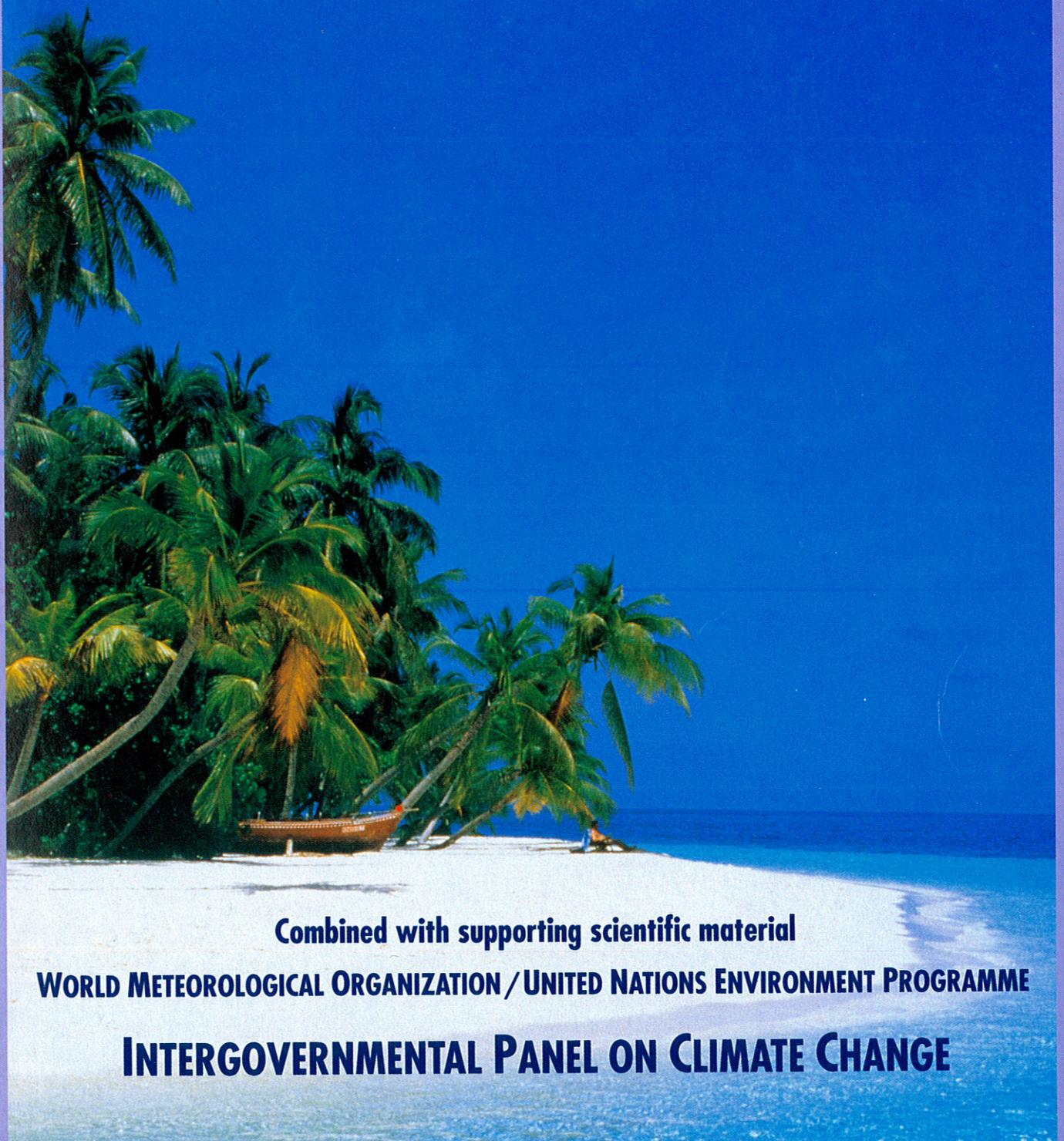


# CLIMATE CHANGE 1992

*The Supplementary Report to  
The IPCC Impacts Assessment*



**Combined with supporting scientific material**

**WORLD METEOROLOGICAL ORGANIZATION / UNITED NATIONS ENVIRONMENT PROGRAMME**

**INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE**



# Climate Change 1992

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The supplementary report to the IPCC Impacts Assessment



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Edited by W J McG Tegart and G W Sheldon

Australian Government Publishing Service  
Canberra

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ISBN 0 644 25150 6

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Published for the Department of the Arts, Sport, the Environment and Territories by the Australian Government Publishing Service, Canberra

Cover illustration: Island in the Maldives (courtesy of Austral International, Sydney)

Printed on 100 per cent recycled paper

Printed in Australia by A. J. LAW, Commonwealth Government Printer, Canberra

Intergovernmental Panel on Climate Change

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# Climate Change 1992

## The Supplementary Report to the IPCC Impacts Assessment

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Report prepared for IPCC by Working Group II

Chairman: Professor Yu A Izrael (Russia)

Co-Vice-chairmen: Professor O Canziani (Argentina), Dr Hashimoto (Japan),  
Professor O S Odingo (Kenya), Dr W J McG Tegart (Australia)



WMO



UNEP



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## Preface by Professor G O P Obasi (WMO) and Dr M K Tolba (UNEP)

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The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme in 1988 under the Chairmanship of Professor Bert Bolin. The Panel formed three Working Groups:

- to assess the available scientific evidence on climate change (Working Group I);
- to assess the environmental and socioeconomic impacts of climate change (Working Group II); and
- to formulate response strategies (Working Group III),

and a Special Committee on the Participation of Developing Countries to promote the participation of those countries in its activities.

The IPCC First Assessment Report was completed in August 1990 and consists of the Overview, IPCC Scientific Assessment, the IPCC Impacts Assessment, the IPCC Response Strategies (the last three including the respective Policymakers' Summary) and the Policymakers' Summary of the IPCC Special Committee. The Report has now become a standard work of reference, widely used by

policymakers, scientists and other experts, and encompasses a remarkable coordinated effort by hundreds of specialists from all over the world.

In March 1991, anticipating a continuing need for the most up-to-date information on climate change and the United Nations Conference on Environment and Development (Rio de Janeiro, June 1992), the Panel requested its three Working Groups to produce updates to their 1990 Reports. The result is the 1992 IPCC Supplement which was completed in February 1992. This volume contains the contribution of Working Group II to support the conclusions in its update of the IPCC Impacts Assessment.

As in 1990, success in producing this Supplement has depended upon the enthusiasm and cooperation of scientists and other experts worldwide. We are grateful for their commitment. We express especial gratitude to Professor Bolin for his very able leadership of the IPCC and once again congratulate Professor Yu A Izrael, Chairman of the Working Group, and his Co-Vice Chairmen (Dr W J McG Tegart, Dr S Nishioka, Professor R S Odingo and Professor O Canziani) for another job well done.

## Preface by Professor Bert Bolin, Chairman, IPCC

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IPCC Working Group II, charged with the assessment of the environmental and socioeconomic impacts of climate change, completed its first report, the IPCC Impacts Assessment, in August 1990. Based on that report and the corresponding reports from Working Groups I and III and its Special Committee on the Participation of Developing Countries, the IPCC last that year agreed on a set of conclusions (Fourth Session, Sundsvall, Sweden, 27-31 August 1990) which were forwarded to the UN General Assembly. Subsequently, an Intergovernmental Negotiating Committee (INC) was established by the General Assembly with the specific charge to negotiate a climate convention to be ready for signature at the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro in June 1992. In March 1991, the IPCC agreed that a supplement to its 1990 report be prepared to assist the INC further in its task.

Analyses of the impacts of climate change are obviously needed as a basis for negotiating measures for prevention or mitigation of the effects of climate change. However, such analyses cannot be successfully carried out until more precise climate change scenarios become available. The prevailing uncertainties in the prediction of likely future changes of climate, particularly on regional scales, therefore represent a major difficulty in pursuit of the task given to Working Group II.

The wide-ranging work done so far by the scientists and other specialists was brought together in the form of detailed analyses by key researchers in the field. On the basis of these analyses, Working Group II prepared its contribution to the 1992 IPCC Supplement which is being presented in this volume together with the underlying supporting material. The latter, however, has undergone full peer review. Even though the findings and conclusions presented in the volume remain qualitative in most in-

stances, they nevertheless provide an important basis for the further scientific work that is required.

The Working Group has also initiated methodological studies which should assist in the further pursuit of its task. The development of methods for sensitivity analysis is of particular importance in this context. This volume also reports on the methodological work.

As Chairman of the IPCC, I am pleased to acknowledge the large amount of work that has gone into the production of the present volume. My particular thanks go to the Chairman of the Working Group, Professor Yu A Izrael, and his Co-Vice-Chairmen (Dr W J McG Tegart, Dr S Nishioka representing Dr M Hashimoto, Dr O Canziani and Professor R S Odingo). The report is the result of the work of a large group of scientists and other experts who have devoted much of their professional time to make this assessment possible. I am very grateful for their efforts and contributions. My thanks are also extended to the IPCC central secretariat at the World Meteorological Organization in Geneva under the direction of Dr N Sundararaman, who has carried out the important function of coordinating the parallel efforts of the three working groups under the constraints of a very tight schedule.

It is most important that the kind of cooperative efforts represented by the work of the IPCC be continued in order to provide the basic information needed to transform the United Nations Framework Convention on Climate Change signed at the UNCED into an effective international instrument for the protection of the global climate for the coming generations of humankind.

Stockholm  
July 1992

## Preface by Professor Yu A Izrael, Chairman, IPCC Working Group II

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The first IPCC Impacts Assessment prepared by Working Group II (WGII) of the IPCC<sup>1</sup> was published in 1990<sup>2</sup>. The report was a comprehensive statement of the state of knowledge concerning impacts of climate change and resulted from almost two years' work by over two hundred scientists worldwide. The report was prepared under the leadership of the WGII Chairman, Professor Yu A Izrael (Russia) and Vice-Chairmen, Dr W J McG Tegart (Australia) and Dr M Hashimoto (Japan).

In the eighteen months since then, scientific activity has continued to focus on the impacts of climate change and progress has been made in a number of important areas. The purpose of this Supplement is to update the 1990 Report, paying particular attention to its key conclusions and to new issues which have appeared in the scientific debate. The Supplement should be read in conjunction with the earlier report.

The conclusions presented in the Supplement are based on the supporting scientific material published here, which has been prepared by leading scientists and exposed to a widespread peer review. It can therefore be considered as a statement of the contemporary views of the international scientific community.

It is clear from the Supplement that comprehensive estimates of the physical and biological effects at the regional level are still difficult to make. Confidence in regional estimates of critical climate factors presented by Working Group I is still low, particularly precipitation and soil moisture. Continued research is necessary to refine the estimates of potential impacts.

The estimates already available suggest that if continued emission of greenhouse gases persisted through

the next century and, in particular, if CO<sub>2</sub> in the atmosphere doubled, there would not be a global catastrophe due to climate change. However, there would be severe impacts in those regions of the world least able to adapt and substantial response measures would need to be taken.

I am pleased to acknowledge the contributions of so many, in particular the Lead Authors who have given so freely of their expertise and time in the preparation of this Report. I am grateful to my Co-Vice-Chairmen, Dr W J McG Tegart (Australia), Dr S Nishioka (Japan), Professor R S Odingo (Kenya) and Professor O Canziani (Argentina) for overseeing the reviewing and publication of the Supplement. Financial support for editing and publication was provided by the Department of the Arts, Sport, the Environment and Territories, Australia, and thanks are due to the staff of that Department for their assistance in compilation and editing of the Supplement, in particular, Ms J Hellyer and Ms M Kimber.

Thanks are also due to all the members of the IPCC central secretariat at WMO, Geneva, under the direction of Dr N Sundararaman, for their friendly and tireless assistance and coordination with the other IPCC Working Groups.

I am confident that this 1992 Supplement will assist further in building the firm scientific foundation necessary for the formulation of a rational and comprehensive response by humankind to the impacts of climate change.

Moscow  
June 1992

1. Organisational details of IPCC and Working Group II are shown in Appendix B.

2. *Climate Change. The IPCC Impacts Assessment*. WJ McG Tegart, GW Sheldon and DC Griffiths (Eds), Australian Government Publishing Service, Canberra, Australia, 1990.



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## Executive summary

### Introduction

Working Group II has examined aspects of four of the tasks approved at the fifth plenary session of IPCC in March 1991. These tasks were:

- prediction of the regional distributions of climate change and associated impacts studies, including model validation studies;
- energy and industry related issues;
- agriculture and forestry-related issues;
- vulnerability to sea-level rise.

From the stimulus provided by the publication in 1990 of the IPCC Impacts Assessment, many regional studies have been carried out on assessment of impacts of climate change. A questionnaire circulated by Working Group II in June 1991 was valuable in revealing new information and in defining areas of common concern to many countries (see Appendix A). Thus, roughly 50% of the responses highlighted the impacts of climate change on hydrology and water resources, emphasising the importance of water in most countries. Other topics of priority interest, particularly for developing countries, were agriculture and forestry, and the world's oceans and coastal zones. Both reflect the apprehension of countries over availability of food supplies from land and sea sources.

Additional areas of concern identified in the questionnaire were desertification (particularly Africa and Asia), cyclones and other extreme events (particularly their economic impacts), and climate variability associated with the El-Niño Southern Oscillation (ENSO) phenomenon, prolonged droughts and extreme events. The national responses showed concern that changes in climate variability as a consequence of climate change may create increased risks, especially in those parts of the world where climate variability is known to have significant social and economic impacts. It is important to note that many countries, particularly in the Southern Hemisphere, also identified increases in UV-B radiation as a significant area of concern.

Working Group II's activities focused only on the portions of the four tasks noted above that directly related to the impacts of climate change and the report should be read in association with the reports of Working Groups I and III. These activities built on the earlier work reported in the first IPCC Impacts Assessment. The previous format

of subgroups dealing with specific topics was maintained and task forces were set up to deal with monitoring and guidelines for assessment of impact.

In view of the extreme concern expressed over impacts of climate change on hydrology and water resources and on changes in UV-B radiation in the responses to the questionnaire, additional work was carried out on those topics although they were not identified in the tasks approved at the fifth IPCC plenary session. Further work was also carried out on the cryosphere in view of its importance to global climate change.

The findings of the subgroups and task forces are reported under the four tasks as:

- prediction of the regional distributions of climate change; this includes:
  - Systematic observations to identify climate change consequences;
  - Preliminary guidelines for assessing impacts of climate change.
- energy and industry-related studies; this includes:
  - Energy; human settlement; transport and industrial sectors; human health; air quality; effects of ultraviolet B radiation.
- agriculture and forest-related issues; this includes:
  - Agriculture and forestry; natural terrestrial ecosystems; hydrology and water resources.
- vulnerability to sea-level rise; this includes:
  - World oceans and coastal zones—ecological effects; terrestrial component of the cryosphere.

*Although all the studies reported here have served to extend our knowledge of the potential impacts of climate change and, to some extent, reduce the uncertainties, they do not radically alter the conclusions of the IPCC Impacts Assessment. Thus, as stated there:*

Any predicted effects of climate change must be viewed in the context of our present dynamic and changing world. Large-scale natural events such as El Niño can cause significant impacts on agricultural and human settlements. The predicted population increase will produce severe impacts on land use and on the demands for energy, fresh water, food and housing, which will vary from region to region according to national incomes and rates of development. In many cases, the impacts will be felt more severely in

regions already under stress, mainly the developing countries. Human-induced climate change due to continued uncontrolled emissions [of greenhouse gases] will accentuate these impacts. . . The severity of the impacts will depend to a large degree on the rate of climate change.

### **Prediction of the regional distributions of climate change and associated impact studies, including model validation studies**

#### *Regional climate change prediction*

The precise prediction of climate change at regional level is subject to great uncertainty. Prediction of precipitation changes is particularly uncertain, although the changes are of great practical significance. Progress in the development of global circulation models (GCMs) is urgently needed, particularly in terms of improving their capability for regional prediction and to understand changes in arid and semi-arid regions. Work on improving regional predictions using the palaeo-analog method continues in Russia and other countries. In the further work of the IPCC, all methods of regional climate prediction should be reviewed and assessed together.

#### *Guidelines for assessing impacts of climate change*

Working Group II has prepared guidelines to assess the socioeconomic and environmental impacts of potential climate change. These guidelines outline a framework for the study of climate-environment-society interactions and the estimation of the impacts of climate change which will allow comparisons and integration of impacts across various geographical areas and economic sectors. Further work will continue as a long-term task.

Impact assessments involve several steps:

- definition of the problem;
- selection of analytical methods;
- testing the method;
- development of climatic and socioeconomic scenarios;
- assessment of potential impacts;
- evaluation of technical adjustments; and
- consideration of policy options.

Definition of the problem includes identifying the specific goals of the assessment, the sector(s) and geographical area(s) of interest, the time horizon of the study, the data needs and the wider context of the work.

Selection of analytical method(s) depends upon the availability of resources, models and data. Impact assessment analyses could range from the qualitative and descriptive to the quantitative and prognostic. Thoroughly testing the method(s), including model validation and sensitivity studies, before undertaking the full assessment is necessary to ensure credibility.

Development of the climatic and socioeconomic scenarios involves several steps. First, the current and projected climatic, socioeconomic and environmental conditions expected to exist over the study period in the absence of climate change should be established. Second, scenarios of regional climate change over the study time frame must also be developed. Third, biophysical and environmental effects should be projected under the altered climate. These projections should then be used, preferably in integrated environment-economic models, to calculate the socioeconomic effects under the altered climate. Assessment of potential impacts of the sector(s) or area(s) of interest involves estimating the differences in environmental and socioeconomic conditions projected to occur with and without climate change.

Projections of effects with and without climate change should incorporate 'automatic' adjustments. However, the impact assessment should seek to evaluate the additional technical adjustments resulting from application of existing and new technologies or practices that may be available over the study period, assuming no change in the current legal and institutional framework.

The costs and benefits of climate change should be assessed, to the extent possible, using a common measure and discounted to net present value. Alternatively, costs and benefits should be described qualitatively. The above general framework would also allow consideration of policy options and their socioeconomic and environmental impacts.

#### *Monitoring to identify climate change consequences*

There is a need to increase the available information and data to support impact studies, particularly in developing countries. This need can be met through enhancing and, where appropriate, establishing integrated monitoring programs including biological, chemical, physical and climatological parameters, as well as constructing concurrent social and economic assessments, at the national, regional and global levels to identify climate change consequences. Data quality needs to be assured and data analyses and their interpretation need to be carried out carefully. The use of common protocols for collection and analysis processes, including Geographical Information Systems (GIS), and for equipment will aid in assuring

intercomparability and further encourage international cooperation. The development of the preliminary IPCC guidelines for assessing the impacts of climate change is an important contribution to this end.

Monitoring of sensitive terrestrial and marine ecosystems, including the cryosphere, and component species should be given priority as they could provide early detection/warning of climate change and its impacts. Also to be given priority are those species and ecosystems which have significant (locally/regionally defined) social and/or economic values. The classic ground station approach (including points, plots and transects) should provide the basic building blocks of monitoring programs; however, these should also be supplemented with remotely sensed observations (eg satellite, radar and photogrammetry). Advantage should also be taken of automatic data transmission and processing systems.

At present, international organisations such as UNEP, WMO and IOC are implementing monitoring programs to help identify ecological and socioeconomic consequences of climate change. UNEP has an initial program for observing terrestrial ecosystems with observations extending on either side of the present boundaries of plant zones for early detection of possible shifts of these boundaries. WMO and IOC, among their many monitoring activities, have designed a satellite observing system for climatic and ocean parameters. Current planning of the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS) should consider the value of including the monitoring of terrestrial and marine ecological impacts of climate change. These can provide an early indication of the integrated effect of climate change.

### Energy and industry-related issues

#### *Energy, human settlement, transport and industrial sectors, human health, air quality and effects of ultra-violet-B radiation*

In terms of human settlement, recent studies for the Maldives and for the Pacific island states including Tuvalu, Kiribati, Tokelau and the Marshall Islands have reconfirmed that small low-lying island states and large populations living in low-lying coastal areas will be increasingly vulnerable to the combination of sea-level rise, storm surges and coastal flooding, particularly if adaptive measures are inadequate.

The high dependency on biomass and hydro-electric energy in many developing countries indicates that these countries are quite sensitive to the impacts of climate change. Biomass production, on which developing coun-

tries depend for much of their energy needs, could be altered by climate change.

On the other hand, there has been little work that has shed new light on the question of socioeconomic impacts in the areas of energy, human settlement, transport and industrial sectors, human health and air quality.

A UK study shows that soil shrinkage as a result of climate change in clay-rich areas has major implications for the construction and insurance industries and for human settlement. Water-dependent industries such as food processing, paper making and power generation could be affected by hydrological changes under changed climate conditions.

Knowledge of climate change on human health has extended and confirmed the previously reported results with greater understanding of potential shifts in disease vector habitats with global warming, particularly in New Zealand and Australia. Diseases such as malaria, lymphatic filariasis, schistosomiasis, leishmaniasis, onchocerciasis (river blindness), dengue fever, and Australian and Japanese encephalitis could increase or be reintroduced in many countries as a consequence of global warming. Regarding the impact of UV-B radiation on health, recent studies have linked UV-B radiation to additional effects that had not been proposed previously, such as those affecting the human immunosuppression system and vision.

### Agriculture and forest-related issues

#### *Agriculture and forestry*

New studies, such as those in the European Community, North America, and Southeast Asia, highlight the conclusions of the IPCC Impacts Assessment that impacts will vary greatly, depending on the extent of climate change and on the type of agriculture. These findings largely amplify, but do not radically alter, the conclusions made in the first IPCC Impacts Assessment. They do, however, confirm that the impact of global warming on agriculture may be serious if warming is at the upper end of the range projected by the IPCC Working Group I.

Recent studies have reinforced concern that drought is the area in which climate change poses the greatest risk for agriculture, and consequently arid and semi-arid regions are likely to be most vulnerable to climate change.

Other recent studies confirm the earlier conclusion that climate change may benefit ecological conditions for insect growth and abundance, which is likely to have a negative effect on crop, livestock and forest production in some regions.

Research continues to address the relative importance of direct and indirect effects of CO<sub>2</sub>, in combination with

a rise in temperatures, on future crop production. While some scientists emphasise enhanced photosynthesis and more efficient water use as seen in controlled settings, others are sceptical that these benefits will arise in farmers' fields under changing climate conditions.

The effects on plant growth may result in the maintenance of present-day soil conditions in some regions, as greater soil organic matter and denser ground cover may counter the effects of soil erosion caused by increased rainfall intensities and oxidation rates of organic matter in soils caused by higher temperatures.

Adaptation to climate change by the existing agricultural production system should be possible, and the worldwide systems of agricultural research should be able to provide new crop cultivars that maintain high yields and nutritional quality. However, efforts will be needed to make such developments available to small farmers in developing countries in time to respond to changes in local climate conditions.

New analyses support the conclusion of the IPCC Impacts Assessment that the impacts of climate change on forests could have significant socioeconomic consequences. This is especially important for those countries and regions where economic and social welfare, and economic development are highly dependent on the forest sector.

Key uncertainties require continued data collection and research for policy development and decision making. These include:

- the extent of managed and natural forests, their spatial and temporal variation and their roles in the global carbon cycle;
- genetics and physiology of tree species and the relationships among subordinate and competitive species;
- regional impacts; and
- the linkages among the regional impacts, socioeconomic structures, and the thresholds and critical limits where changes take place.

#### *Natural terrestrial ecosystems*

Analyses subsequent to those included in the IPCC Impacts Assessment reinforce the conclusion that natural terrestrial ecosystems could face significant environmental impacts as a result of the global increases in atmospheric concentrations of greenhouse gases and associated climatic changes. In particular, these studies continue to suggest that the rate of these changes will be the major factor in determining the type and degree of impacts, with a variety of responses expected for different regions and for different communities within ecosystems. Current climatic projections continue to suggest that rates of change are

likely to be faster than the ability of some component species to respond, and that the responses of species and ecosystems may be sudden, potentially leading to ecosystem destabilisation or degradation.

The promotion of heightened public awareness of the general values of natural terrestrial ecosystems is essential to gaining public support for sustaining these ecosystems in a changing climate. Particular emphasis should be placed on involving ecosystem managers and local people in the assessment of the impacts, consequences and response strategies.

One of the major issues regarding the impacts of climate change on terrestrial ecosystems is water availability, with recent studies suggesting that while water use efficiency of vegetation could increase in an enriched CO<sub>2</sub> atmosphere, the same amount of water per unit soil area may be necessary because of increased leaf area ratios due to greater biomass produced in that enriched atmosphere.

Projected climate changes are expected to result in an accelerated reduction of tropical forest on the African continent and an encroachment of the Sahel syndrome into the savannas. These changes could worsen the already precarious production systems in the affected regions of Africa, further stressing the associated natural ecosystems and component species. Degradation of wetlands and shallow lakes (eg within savanna ecosystems in Africa and within the Great Plains of North America) as a result of projected decreases in rainfall or soil moisture could adversely impact on resident animals and migratory species.

With projected climate change, profound impacts, both beneficial and destructive, can be expected for the distribution and productivity of valuable fisheries and the industries associated with them. The added stresses to freshwater ecosystems as a result of climate change can be expected to reduce species numbers and genetic diversity within freshwater populations in the short term. By contrast, with warming, a longer growing season could lead to greater fish productivity where temperature is currently a limiting factor.

Uncertainties and gaps in the knowledge base continue to exist in terms of our understanding of the environmental impacts and associated socioeconomic consequences of climate changes. National, regional and global efforts need to be cooperatively concentrated on reducing these deficiencies, which primarily exist as a result of the lack of sufficient information and data on:

- fundamental ecological processes;
- the links between climate and atmospheric chemistry on the one hand and the response of natural terrestrial ecosystems and their component species on the other; and

- the links between natural terrestrial ecosystem changes and social and economic welfare under a changing climate.

In particular, there is a lack of information on the sensitivity of these ecosystems and their component species to climate change, the vulnerability of social and economic systems to ecosystem changes, and thresholds/critical levels for these ecosystems and associated social and economic systems. Existing international programs such as GEMS and MAB can provide one means of examining these deficiencies.

### *Hydrology and water resources*

Since the publication of the IPCC Impacts Assessment, several studies on impacts of climate change on hydrology and water resources have been conducted. Unfortunately, there is not yet adequate information on regions affected by aridity and desertification; efforts should be made to fill that gap. The new studies expanded on the geographic scale of the original surveys and confirmed many previous conclusions, but few new insights were offered on hydrologic sensitivities and vulnerability of existing water resources management systems.

The principal conclusions suggested by the new studies are:

- Significant progress has been made in hydrologic sensitivity analyses in developed countries, yet large gaps exist in the information base regarding the implications of climate change for less developed nations;
- Comparative sensitivity analyses that rely on existing GCMs offer generic insights regarding the physical hydrologic effects and water resources management impacts, but the differences in the outputs of the GCMs coupled with large differences in hydrologic sensitivity analyses make it difficult to offer region-specific impact assessments;
- Temporal streamflow characteristics in virtually all regions exhibited greater variability and amplification of extremes, with larger flood volumes and peak flows as well as increased low flow episodes and a shift in the turning of the seasonal runoff;
- The higher the degree of water control, regulation and management of sectoral water demands, the smaller the expected adverse effects of global warming. Conversely, unregulated hydrologic systems are more vulnerable to potential hydrologic alterations.

The principal recommendations are:

- Increased variability of floods and droughts will require a re-examination of engineering design assumptions, operating rules, system optimisation, and contingency planning for existing and planned water management systems;
- More studies on hydrologic sensitivity and the vulnerability of water resource management need to be focused in arid and semi-arid regions and small island states;
- A uniform approach to the analyses of hydrologic sensitivity to climate change needs to be developed for comparability of results.

### *Vulnerability to sea-level rise*

#### *World oceans and coastal zones: ecological effects*

Since the first IPCC Impacts Assessment, new studies reconfirm that rising sea-level is of more concern in low-lying coastal ecosystems than rising water temperatures. However, the combination of sea-level rise and temperature rise, along with changes in precipitation and UV-B radiation, are expected to have strong impacts on marine ecosystems, including redistributions and changes in biotic production.

The impact of sea-level rise depends on the total net rise resulting from the relative vertical movements of the land and of the sea. In areas undergoing natural eustatic uplifting of the land due to tectonic plate movement, glacial rebound, and vulcanism, there will be little relative rise of sea-level. In land areas that are naturally falling, as in the south-eastern USA, because of tectonic and compaction forces, impacts of sea-level rise will be more important.

A new study of the Bering Sea indicates that in areas without natural land uplift, there could be important impacts where there is a high density of marine organisms dependent on certain types of onshore and near-shore marine environments that may be affected by sea-level change. Nevertheless, sea-level rise is of far less consequence in northern areas than are other impacts of climate change to northern ecosystems and to global carbon cycling. These regions are very important in the global carbon cycle and a small temperature rise may cause significant increases in bioproductivity and in carbon flux to the oceans.

Coral organisms grow 1–20 cm/year and reef growth rates as a whole are known to be up to 1.5 cm/year. Not all reefs accumulate at these rates, but most should keep pace with the expected rise in sea-level if other factors do

not alter growth conditions. Stress on the reefs from other variables (storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, mass mortality in algal grazers etc) may prevent some reefs from keeping pace with rising sea-level, resulting in changes to near-shore hydrodynamics.

With respect to temperature rise, marine organisms in the tropics live closer to their maximum thermal tolerance than those in more temperate climates. Although a 1–2°C temperature rise would raise summertime mean temperature to over 30°C over much of the tropical/subtropical region, most migratory organisms are expected to be able to tolerate such a change. Temperature rise may trigger bleaching events in some corals, but it is expected that the other stresses mentioned above will be more important.

Intertidal plants, such as mangroves, can withstand high temperature and, unless a rise in temperature affects reproduction, it is unlikely to have any effect. Because mangroves grow best in moderately saline environments, mangroves can probably keep pace with sea-level rise in rain-fed humid areas, but may be over-stepped and abandoned in more arid areas, particularly if inland retreat is not possible. Thus, future changes in patterns of rain and runoff and of overcutting may be more important than sea-level rise. With respect to marshes, new studies indicate that mid-latitude plants seem to tolerate salinity better and are more productive under elevated CO<sub>2</sub>.

New findings of WMO/UNEP indicate that UV-B radiation reaching oceanic and coastal zone environments will increase faster than expected when the first IPCC Impacts Assessment was written. Since so many marine resources spend all or substantial parts of their lives near the water surface, there is a significant threat to some fisheries. The first assessment expressed concern about leaching of contaminants during sea-level rise from coastal waste disposal sites. There are also bacteria and viral agents in such sites and in coastal septic sewerage systems which could be increasingly released into coastal waters. There are potential impacts on coastal resources, but the primary concern is for the humans who consume them and the loss of commerce owing to the closure of fish and shellfish areas by health authorities. Lastly, potential changes in storm frequency or intensity could have important ecological consequences to coastal resources.

### *Cryosphere*

Analyses continue to support the conclusion that projected changes in climate associated with enhanced atmospheric concentrations of greenhouse gases are expected to reduce substantially the areal extent and volume of seasonal snow cover, mountain glaciers, terrestrial ice sheets and frozen

ground including permafrost and seasonally frozen ground.

Recent analyses have shed some further light on the potential impacts for these elements of the terrestrial cryosphere:

- analysis of satellite-derived data on snow cover has shown the extent of snow in the Northern Hemisphere to be at record low levels since the middle of 1987, with the largest negative anomalies occurring in the spring;
- above normal temperatures throughout much of the Northern Hemisphere in 1989 led to the initiation of extensive active layer detachment slides within permafrost in some regions of the Canadian and Russian Arctic with damming and degradation of water quality in affected streams and further failures initiated;
- emissions of methane from hydrates in Arctic regions as a result of permafrost degradation may have been underestimated;
- there is some evidence to suggest that glaciers in the Northern Hemisphere polar and subpolar regions are receding at a slower rate than previously suggested with some having advanced in the past thirty years. Although the Southern Hemisphere record is not as detailed, records for several New Zealand glaciers show that they have retreated since the mid 1800s, with the suggestion that this has been the result of an increase in temperature and an accompanying decrease in precipitation.

Key uncertainties are associated with understanding fundamental cryological processes, the relationship among these elements (eg impacts of changes in snow cover on permafrost and glacier dynamics), the impacts of climate change on these elements of the cryosphere, the interdependency of associated ecosystems (eg soil erosion and stability changes associated with permafrost degradation) and human systems (eg structures, transportation, transmission lines), and the role of the cryosphere in local, regional and global climate and climate change.

### **Summary of issues for further consideration**

#### *Regional climate predictions*

IPCC has continued to stress that research leading to information on likely regional climate change (and its association with global change) is of the highest priority, and has noted that there are certain aspects of regional climate change that are particularly important in some areas. Among these are tropical cyclones and the tidal surges associated with such storms. Guidance on likely

changes in frequency, intensity and distribution of such events, as a result of climate change, is urgently needed in states in and bordering the Pacific, Indian and Atlantic Oceans. Special attention should be given to the needs of small island states which are particularly vulnerable to climate change. Prediction of regional precipitation is another area of particular concern. Further, the connections between local, regional and global pollution require further study.

The question of the validity of the technique of palaeo-analog for the prediction of regional climate change needs further debate. Although palaeo-data concerning past climates are of great value, clear analogs from the past which can be applied to future climate changes have not yet been identified. In the further work of the IPCC, all methods of regional climate prediction should be reviewed and assessed on a continuing basis.

#### *Country studies and methodologies*

IPCC has recognised the valuable work on methodologies for country studies—such as that for national inventories of greenhouse gas emissions and sinks—which were being carried out by the three Working Groups and elsewhere. It has acknowledged that this is a cross-cutting issue. It has recognised the utility of further work on methodologies for both limitation and adaptation and, in particular, their integration into a broader framework.

Priority should be given to assessing the work in progress and to the development of coherent guidelines for country studies, keeping in mind the circumstances of different countries and the evolving nature and pattern of their use of natural resources. The next step in this process should be the convening of a workshop, possibly before the eighth session of IPCC, with a report to be reviewed at that time.

#### *Dissemination of IPCC information*

With financial support provided by some countries, the IPCC has conducted a series of information exchange seminars in several developing countries, and the IPCC Impacts Assessment and some other IPCC reports have been translated into several languages. Non-government organisations are also contributing significantly to the dissemination of information on climate change. The seminars have attracted participation from all levels of society, including heads of state and government ministers, specialists, experts, non-government organisations and the public. They have contributed significantly to the understanding of the various aspects of the climate change issue. Further seminars in developing countries should be undertaken in response to requests, but are dependent on the availability of financial and human resources.

#### *Resource issues*

The IPCC assessments are critically dependent on research and development carried out under international programs and by national research teams. The need to increase these research efforts has become obvious in the course of the IPCC work. At all levels of society, there is insufficient knowledge and understanding of both the climate change issue itself, as well as all the socioeconomic impacts and further societal implications. The IPCC strongly urges that greater means be made available for these activities and that the major international global programs be given adequate resources. It is particularly important that means are made available to permit developing countries to become genuine partners in this global research effort. The progress of our understanding is dependent upon dealing with the global environment in its entirety.

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# A

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## Prediction of the regional distribution of climate change and associated impact studies, including model validation studies

The work carried out under this task is discussed under the headings of:

Systematic observations to identify climate change consequences

Preliminary guidelines for assessing impacts of climate change

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# I Systematic observations to identify climate change consequences

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# I Systematic observations to identify climate change consequences

## 1 Introduction

In accordance with the decision of the IPCC (Fifth Session, Geneva, 13–15 March 1991), IPCC Working Group II was given the task of identifying the regional/national components of systematic observation programs which could be used for climate change impact studies. An Expert Group, chaired by Professor Yu Izrael with representatives from Argentina, Canada, France, India, Japan and Norway, was established at the fourth session of WGII to carry out this task.

This report records the preliminary findings of this Expert Group. It comprises a summary of potential impacts of climate change as identified by the IPCC (providing the framework for required systematic observations) and a preliminary assessment of the required elements of systematic observation programs to support research on the environmental impacts and socioeconomic consequences of climate change.

## 2 Potential impacts of climate change

Working Group I of the IPCC has prepared an authoritative and strongly supported statement on climate change. The IPCC Scientific Assessment identifies those aspects of climate change issues of which the scientific community is relatively certain and also those for which uncertainties still exist. Uncertainties in the predictions of climate change, particularly those concerning timing, magnitude and regional patterns of climate change, are associated with imperfect knowledge of:

- future rates of man-made emissions;
- how these will change the atmospheric concentrations of greenhouse gases (GHG); and
- the response of climate to these changed concentrations.

It is clear from the IPCC Impacts Assessment, however, that the potential implications of climate change, under doubled CO<sub>2</sub> scenarios, are likely to be far-reaching. Climate change is likely to result in:

- changes in the amount of precipitation and in soil moisture;
- changes in the boundary zones of vegetation, particularly in northern, high-latitude areas (tundra and boreal forest areas may be significantly reduced);
- a significantly altered hydrological regime;
- increased annual runoff at high latitudes;
- altered agricultural potential, both for areal extent of arable land and the crop types;

- changes in the aerial extent and mass of glaciers;
- decreases in glaciers over Antarctica, Greenland and the Arctic islands;
- reduced volume of high-mountain glaciers;
- degradation of permafrost;
- sea-level rise, with implications for coastal and island ecosystems and structures; and
- hydrophysical, hydrochemical and biological processes of the oceans and seas such as ice regime, intensity of bioproduction, redistribution of productive ocean zones, and changes in the formation of commercial fish stock.

The IPCC Impacts Assessment concluded that these impacts will not necessarily be steady, that surprises cannot be ruled out, and that the severity of the impacts will depend to a large degree on the rate of climate change.

The IPCC Impacts Assessment also concluded that uncertainties exist in our knowledge of the environmental impacts and socioeconomic consequences of climate change, particularly at the regional level and in areas most vulnerable to climate change. These uncertainties are to a large extent related to a lack of available supportive data and information at the regional level. To deal with these deficiencies, national, regional and international efforts directed at initiating and maintaining integrated systematic observation programs for terrestrial and marine (managed and unmanaged) ecosystems are required.

Tables 1 and 2 list physical, chemical and biological elements which should be included in systematic observation programs directed at providing an integrated set of data and information for impact assessments.

## 3 Existing systematic observation programs

At present, international organisations such as UNEP, WMO, IOC and UNESCO have a number of programs to monitor physical, chemical and biological elements. Some of these, such as UNEP's Global Environmental Monitoring System (GEMS) were developed in the mid 1970s, with a number of improvements having taken place since. The Climate System Monitoring (CSM) Project of the World Climate Data Programme (WCDP) was initiated in 1984 and has been designed to provide information on the state of the climate system and diagnostic insights into significant large-scale anomalies of regional and global consequence.

The Second World Climate Conference (1990) stressed the urgent need to develop a Global Climate Observing System (GCOS), which would provide comprehensive information on the total climate system, involving a multi-

disciplinary range of physical, chemical and biological properties and atmospheric, oceanic, hydrologic, cryospheric, and terrestrial processes. GCOS is intended to meet the needs for:

- climate system monitoring;
- climate change detection and systematic observations of the responses to climate change, especially in terrestrial ecosystems and mean sea-level;
- data for application to national economic development; and
- research towards improved understanding, modelling and prediction of the climate system.

GCOS will build, as far as possible, on existing operational and scientific observation, data management and information distribution systems, and on further enhancement of these systems. GCOS is to be based upon improved World Weather Watch systems and the Integrated Global Ocean Services System, data communication and other infrastructures necessary to support operational climate forecasting and the establishment of a Global Ocean Observing System for physical, chemical and biological measurements. In addition, it will require the maintenance and enhancement of programs systematically observing other key components of the climate system, such as the distribution of important atmospheric constituents (eg the Global Atmospheric Watch which includes BAPMoN and G0305), terrestrial ecosystems (including the International Geosphere-Biosphere Programme), as well as clouds, the hydrological cycle, the earth's radiation budget, ice sheets and precipitation over the oceans (including the World Climate Research Programme).

The Climate Change Detection Project is a recent initiative; begun in 1991, its primary objective is to provide regularly updated estimates of climate change on a global and regional basis, and an assessment of the relative importance of these changes. In time, it is hoped that the assessments will enable the delineation of any climate change signal from the background noise of natural climate variability.

There is a number of international organisations implementing systematic observation programs that could be used to support efforts directed at identifying ecological impacts and socioeconomic consequences of climate change, including:

- an initial UNEP program for observing terrestrial ecosystems with observations extending on either side of the present boundaries of plant zones for early detection of possible shifts of these boundaries;
- the Arctic Monitoring and Assessment Programme (AMAP), now under development, which will monitor

and assess background pollution of all major arctic environments, and includes systematic observations of CO<sub>2</sub> and other radiatively active gases; AMAP will also assess fluctuations of the ozone layer, and compare variations in regional climates with those globally.

- a Global Ocean Observing System (GOOS) which is being developed to meet the needs of global climate research, monitoring and prediction; it will be based on long-term systematic observations of physical, chemical and biological processes of the World Ocean; implementation will be phased-in over the next decade or two, and will provide for the description of, for example, the global circulation of heat and water in the ocean, and their exchange with the atmosphere.

Other international systematic observation programs include those of the Long Term Ecological Reserves and the Biospheric Reserves of the Man and the Biosphere (MAB) programme. National environmental systematic observation programs (related to wider international efforts) such as the UK Environmental Change Network (ECN), Chinese Ecological Research Network (CERN) and Scandinavian networks also exist. These programs, while not geared specifically to climate change impacts, contain some elements which are relevant to that purpose.

#### 4 Recommendations

In spite of recent improvements, present programs for systematic observations of the atmosphere, land surfaces and oceans are, for the most part, insufficient to meet the requirements of data to support research directed at identifying environmental impacts and socioeconomic consequences of climate change. They are also insufficient to support efforts directed at achieving sustainable national economic and social development and to support research towards improved understanding, modelling and prediction of the climate system (eg WCRP and IGBP). Future enhancements of these programs should be directed at increasing their effectiveness and efficiency. These enhancements, therefore, will need to include an appropriate mix of both traditional (on-site) and remote sensing technologies. In particular, an enhanced satellite observation system will be essential to observe large and remote areas systematically, including the oceans, as well as sparsely populated arid and semi-arid areas of the world.

The existing programs identified above are but a few examples that can provide the required data for the assessment of regional climates and ecosystems. Notable deficiencies in areal coverage of these programs include tropical forests, savanna, oceans, polar, mountainous

(particularly in developing countries) and arid and semi-arid regions of the globe. The terrestrial areas where gaps exist are largely unmanaged ecosystems and many of these are undergoing major upheaval and changes as a consequence of human interference and growing populations. Data information that could be used to increase understanding of the implications of climate change for these ecosystems and associated human systems is of particular importance.

There are two strategies that could be adopted for systematic observation programs directed at providing the data and information required for identifying environmental impacts and socioeconomic consequences: long-term integrated systematic observations of the state of terrestrial and marine (managed and unmanaged) ecosystems along with associated social and economic parameters; or systematic observations of individual physical, biological and ecological parameters as well as associated social and economic parameters.

In developing the appropriate strategy, use should be made of indices which clearly are indicative of changes in climatic factors, for example, changes in the spatial or temporal boundaries of vegetation, species distribution, and snow or ice cover, and changes in the level of the oceans.

The establishment and maintenance of supportive data and information systems (including the necessary archives) at the national, regional and international levels will be major undertakings. There are deficiencies in the state of systematic observational systems and related data management and analyses capabilities in many countries; these deficiencies are particularly acute within developing countries. The deficiencies can be met by upgrading networks and equipment, and the skills of technicians and scientists.

The availability of coincident and supportive social and economic data and information is essential for climate change impact assessments. Climate change can have both direct impacts and indirect impacts (eg biological or physical responses to climate change which, in turn, lead to socioeconomic impacts on affected human systems). To identify a broader understanding of these impacts, it is important that in addition to and coincident with physical and biological observations, that social and economic parameters/indices also be collected and archived. Having available data and information on the responses of social and economic systems to climatic changes and/or dependent physical and biological changes will enhance understanding and quantification of the interaction processes and will thereby provide a sounder basis for formulating meaningful national response strategies, including adaptation strategies. Table 3 is a preliminary attempt to present the relationships between the required data elements.

Future work in defining the data and information needs to support environmental impacts and socioeconomic consequences activities should be undertaken by the IPCC based on this preliminary analysis and IPCC development of guidelines for climate change impact assessments. Means and modalities of implementation through which efficiency of supportive systematic observation programs can be increased (eg sharing among relevant international and national networks) need to be examined further and, therefore, should be an essential component for subsequent work. Subsequent assessments should also include identifying general principles to guide systematic observation program development so that the resulting programs could support research on environmental impacts and socioeconomic consequences of climate change.

Table 1. Provisional listing of climatic system elements

<i>Climate system state characteristics</i>	<i>Priority</i>	<i>Climate system state characteristics</i>	<i>Priority</i>
1. Atmosphere		1.6. Radiation and cloudiness	
1.1. Surface atmosphere		- cloudiness	****
- surface air temperature (SAT)	*****	- albedo	****
- precipitation over land	*****	- atmosphere transparency	****
- precipitation over ocean	**	- direct solar radiation	****
- air humidity	*	- scattered radiation	***
- sea-level pressure	***	- total radiation	***
1.2. Free atmosphere		- radiation balance	***
- air temperature	****	- outgoing long-wave radiation	****
- humidity	*	2. Atmosphere-ocean interface	
- wind	***	- sea surface temperature	*****
- isobaric surface geopotential	****	- salinity	***
1.3. Circulation and synoptic-climatic systems		- heat, moisture and momentum fluxes	**
- energy	***	- wind velocity	**
- heat, moisture and momentum transport	**	- wave information	*
- atmosphere-action centres (AAC)	***	- sea-level	*
- circumpolar vortex	****	3. Atmosphere-land interface	
- altitude frontal zone	****	- soil temperature	**
- cyclones and anticyclones	****	- soil moisture	***
- circulation indices	****	- heat, moisture and momentum fluxes	*
- blocking indices	****	- lakes (inland waterbodies)	*
- monsoons	*	4. Abyssal ocean	
- tropical cyclones	*	- water temperature	****
- intratropical convergence zone, tropical shower	*	- salinity	***
- El-Niño/southern oscillation	***	- current	*
- telecommunication indices	**	5. Cryosphere	
- quasibiannual cycling in the equatorial stratosphere	**	- snow cover	****
- stratospheric warming	*	- continental ice	***
- intraseasonal 30-60 day-variations	*	- permafrost	*
1.4. Extreme events		- sea ice	****
- droughts and supermoisture periods	****	- soil moisture	****
- severe winters	****	6. Biosphere, ecological effects	
- floods	*	- biomass	-
1.5. Atmosphere composition		- desertification, deforestation	-
- GHG concentrations (CO <sub>2</sub> etc)	****	- yield	-
- aerosol	***	- phenological parameters	***
- ozone	***	7. Geophysical and astronomic factors	
		- Earth's rotation rate	***
		- poles movement	-
		- solar and geomagnetic activity	-
		- volcanoes	-

Priorities denoted through:

\*\*\*\*\* highest: basic component of observation program;

\*\*\*\* should be component of initial observing program;

\*\*\* should be included at the subsequent stages of development;

\*\* possible element for inclusion to improve the observation program;

\* other author's reference;

- need for further assessment to determine priority.

**Table 2. Provisional list of elements**

1. Impact of increased atmospheric CO<sub>2</sub> and climate change on terrestrial ecosystems.
  - 1.1. Plant response to increased CO<sub>2</sub> carbon budget.
    - Carbon budget
    - Interaction between CO<sub>2</sub> and temperature and natural environment stress
    - Plant-plant interaction
    - Vegetation-animal interaction
    - Ecosystem response to increased CO<sub>2</sub>
  - 1.2. Ecosystem response to changed temperature and humidity
    - Carbon budget
    - Phenology and aging
    - Biological diversity
    - Health and productivity
    - Vegetative community composition
    - Models of ecosystems response to climate change
    - Modelling of global response based on vegetation-climate interaction
    - Palaeo-ecological evidence
2. Impact of changed terrestrial ecosystems on climate system
  - Deforestation
  - Afforestation and reforestation
  - Eutrophication and pollution
  - Reforestation/afforestation as means of reducing atmospheric CO<sub>2</sub> concentrations
3. Methane and nitrous oxide fluxes
4. Ecosystem change and regional hydrological cycles
5. Marine ecosystems
  - Community responses
  - Land-ocean interactions
  - Atmosphere-ocean interactions
  - Carbon system and biological pump

**Table 3. Provisional list of elements to be included in systematic observation programs to support environmental impacts and socioeconomic consequences research**

- |   |   |
|---|---|
| <p>Environmental impacts</p> <p>Socioeconomic consequences</p> <p>Observational elements</p>  | <p>Emission of carbon dioxide and methane as a result of permafrost degradation.</p>  |
| <p>I. Changes in the boundaries of natural climatic zones</p> <ol style="list-style-type: none"> <li>1. Changes in the structure of agriculture productivity;           <ul style="list-style-type: none"> <li>Areas under various agricultural crops;</li> <li>Areas of grazing;</li> <li>Areas of desertification;</li> <li>Yield and incomes associated with different crops;</li> <li>Disease and pest occurrences;</li> <li>Rural vs Urban populations and incomes (trends);</li> <li>Emissions and sinks of GHGs due to the loss and accumulation of carbon in soils, methane emissions by livestock, decomposition of nitrogen fertilisers.</li> </ul> </li> <li>2. Changes in the structure of forestry           <ul style="list-style-type: none"> <li>Productivity and health of forests;</li> <li>Areas under various forest species;</li> <li>Fire, pest and disease occurrence;</li> <li>Demographic and income trends for forest communities;</li> <li>Emissions and sinks of GHG due to accumulation of carbon in soils and forest management practices.</li> </ul> </li> <li>3. Changes in the structure of territories and human activities as a result of permafrost degradation           <ul style="list-style-type: none"> <li>Areas with permafrost;</li> <li>Areas of water occurring within permafrost zones;</li> <li>Areas affected by permafrost degradation,</li> <li>Changes in areas used as natural habitats;</li> <li>Disruption of human settlements, infrastructure, and oil and gas pipelines;</li> <li>Costs of refurbishing or relocation of human structures;</li> </ul> </li> </ol> | <p>4. Changes in the structure of natural ecosystems impact on biological diversity           <ul style="list-style-type: none"> <li>Productivity and health of natural ecosystems and their component species;</li> <li>Areas occupied by plant and animal species;</li> <li>Economic implications (eg recreation, tourism and indigenous crafts).</li> </ul> </p> |
| <p>II. Sea-level rise</p> <ol style="list-style-type: none"> <li>1. Changes in human settlements and related infrastructure           <ul style="list-style-type: none"> <li>Areas of island and coastal flooding;</li> <li>Disruption of human settlements;</li> <li>Disruption of transport and other infrastructure;</li> <li>Productive area of land loss;</li> <li>Number of people relocated and associated costs;</li> <li>Costs of relocating, protection and refurbishing of water, sewage and transport systems.</li> </ul> </li> <li>2. Changes in associated natural ecosystems           <ul style="list-style-type: none"> <li>Area and number of beach areas impact;</li> <li>Area and number of coastal ecosystems impacted;</li> <li>Areas lost and/or associated protection costs.</li> </ul> </li> </ol>   |   |

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## II Preliminary guidelines for assessing impacts of climate change

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## II Preliminary guidelines for assessing impacts of climate change

### 1 Objectives

#### 1.1 Purpose of this report

In August 1991, Working Group II, in its Fourth Plenary, agreed on the importance of developing guidelines for assessing the impacts of climate change. This report is a preliminary statement on approaches to climate impact assessment, with particular emphasis on assessing the possible impacts of future change in climate due to the enhanced greenhouse effect. There is little experience with evaluating the social and economic impacts of climate change, so the report deals with these only cursorily. It is desirable that future versions address these topics in more detail. The report does not aim to prescribe a single preferred method, but provides an analytical outline that comprises a number of steps. A range of methods is identified at each step. Where possible, the merits and drawbacks of different methods are briefly discussed, with some suggestions on their selection and use.

#### 1.2 Purpose of climate impact assessment

There are many reasons for conducting climate impact assessments, but the ultimate objective of such assessments is to provide the public and policy makers with estimates of the extent to which climate change may affect the environment and human activities and result in changes in social and economic welfare. The role of assessments is to assist in the development and evaluation of alternative strategies for managing human activities under changeable climatic conditions.

#### 1.3 Methods of assessment

A general framework for conducting a climate impact assessment is shown in Figure 1. It consists of the following steps:

- definition of the problem;
- selection of the method;
- testing the method;
- selection of scenarios;
- assessment of impacts;
- evaluation of adjustments; and
- consideration of policy options.

The first five steps can be regarded as common to most assessments. The last two steps may be included in some studies. The steps are consecutive (single arrows), but the

framework also allows for the redefinition and repetition of some steps (double arrows). At each step, a range of study methods is available. These are described and evaluated in the following sections. For reasons of brevity, however, only the essence of each method is introduced, along with references to sources of further information.

### 2 Definition of the problem

A necessary first step in undertaking a climate impact assessment is to define precisely the nature and scope of the problem to be investigated. This usually involves identifying the goals of the assessment, the sector(s) of interest, the spatial and temporal scope of the study, the data needs, and the wider context of the work.

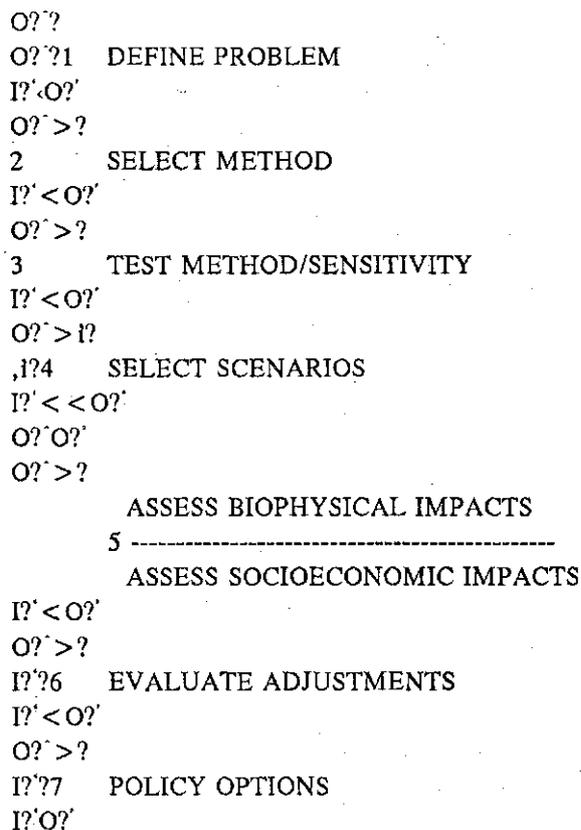


Figure 1: Seven steps of climate impact assessment

#### 2.1 Goals of the assessment

Some general reasons for conducting an assessment were outlined in Section 1.2. Once the general goals are clearly defined, it is important to be precise about the specific

objectives of a study, as these will affect the conduct of the investigation. For example, an assessment of the hydrological impacts of future climatic change in a river catchment would have quite different requirements for data and expertise if the goal is to estimate the capacity for power generation, from those required to predict changes in agricultural income as a result of changes in the availability of water for irrigation.

## 2.2 Sector to be studied

The sector(s) to be assessed determine, to a large degree, the type of researchers who will conduct the assessment, the methods to be employed and the data required. Studies can focus on a single sector or activity (eg agriculture, forestry, energy production or water resources), several sectors in parallel but separately, or several sectors interactively.

## 2.3 Study area

The selection of a study area is guided by the goals of the study and by the constraints on available data. Some options are reasonably well defined, including governmental units, geographical units, ecological zones, and climatic zones. Other options requiring more subjective selection criteria include sensitive regions and representative units. Sensitive regions (eg tree line, coastal zones, ecological niche, marginal community) are selected because of their inherent sensitivity to external forcing such as climate change, and are where changes in climate are likely to be felt first and with the greatest effect. Representative units may be chosen according to any of the above criteria, but in addition are selected to be representative of that regional type and thus amenable to generalisation. For instance, a single river catchment may serve as a useful integrating unit for considering impacts of climate on water resources, agriculture, forestry, recreation, natural vegetation, soil erosion and hydro-electric power generation. Information from this type of study may then be applicable to other similar catchments in a region.

## 2.4 Time frame

The selection of a time horizon for study is also influenced by the goals of the assessment. For example, in studies of industrial impacts the planning horizons may be 5-10 years, investigations of tree growth may require a 100-year perspective, while considerations of nuclear waste disposal may accommodate time spans of well over 1000 years.

However, as the time horizon widens, the ability to project future trends accurately declines rapidly. Most climate projections rely on general circulation models (GCMs), and are subject to great uncertainties over all projection periods. The only prediction horizon of proven reliability is that provided by weather forecast models extending for days or, at most, weeks into the future. In general, few credible projections of socioeconomic factors such as population, economic development and technological change can be made for periods exceeding 15-20 years.

## 2.5 Data needs

The availability of data is probably the major limitation in most impact studies. The collection of new data is an important element of some studies, but most rely on existing sources. Thus, before embarking on a detailed assessment, it is important to identify the main features of the data requirements, namely the variables for which data are needed, the time period, spatial coverage and resolution of the required data, the sources and format of the data and their quantity and quality, and the data availability, cost and delivery time.

## 2.6 Wider context of the work

Although the goals of the research may be quite specific, it is still important to place the study in context with respect to, first, similar or parallel studies that have been completed or are in progress; second, the political, economic and social system of the study region; and third, other social, economical and environmental changes occurring in the study region. Consideration of these aspects may assist policy makers in evaluating the wider significance of individual studies.

## 3 Selection of the method

A variety of analytical methods can be adopted in climate impact assessment, ranging from qualitative descriptive studies, through more diagnostic and semi-quantitative assessments, to quantitative and prognostic analyses. Any single impact assessment may contain elements of one or more of these types. Four general methods can be identified: experimentation, impact projections, empirical analog studies and expert judgment.

### 3.1 Experimentation

In the physical sciences, a standard method of testing hypotheses or of evaluating processes of cause and effect is through direct experimentation. An example is the behaviour of plant species under controlled conditions of climate and atmospheric composition. In the context of climate impact assessment, however, experimentation has only a limited application. Clearly it is not possible physically to simulate large-scale systems such as the global climate, nor is it feasible to conduct controlled experiments to observe interactions involving climate and human-related activities. Only where the scale of impact is manageable, the exposure unit (ie anything exposed to a given climate event) measurable, and the environment controllable, can experiments be usefully conducted.

The information obtained from experiments, while useful in its own right, is also invaluable for calibrating models which are to be used in projecting impacts of climatic change (see below).

### 3.2 Impact projections

One of the major goals of climate impact assessment, especially concerning aspects of future climatic change, is the prediction of future impacts. A growing number of model projections has become available on how global climate may change in the future as a result of increases in greenhouse gas (GHG) concentrations (eg see IPCC 1990a). A main focus of much recent work has been on impact projections, using an array of mathematical models to extrapolate into the future. In order to distinguish them from 'climate models', which are used to project future climate, the term 'impact model' has now received wide currency. First-order effects of climate are usually assessed using biophysical models, second- and higher-order effects using a range of biophysical, economic and qualitative models. Finally, attempts have also been made at comprehensive assessments using integrated systems models.

#### 3.2.1 Biophysical models

Biophysical models may be used to evaluate the physical interactions between climate and an exposure unit. There are two main types: empirical-statistical models and simulation models. Empirical-statistical models are based on the statistical relationships between climate and the exposure unit. Simulation models make use of established physical laws and theories to express the dynamics of the interactions between climate and an exposure unit. The use of these in evaluating future impacts is probably best

documented for the agricultural sector (eg see WMO 1985) and the hydrological aspects of water resources (eg WMO 1988) but the principles can easily be extended to other sectors.

#### 3.2.2 Economic models

Economic models of several types can be employed to evaluate the implications of first-order impacts for local and regional economies. Although their application in climate impact assessment has been advocated for many years, few have actually been used. The main classes of models are microsimulation models, market models and economy-wide models.

#### 3.2.3 Integrated systems models

Integrated systems models represent an attempt to combine elements of the modelling approaches described above into a comprehensive model of a given regionally or sectorally bounded system. No fully integrated systems model has yet been developed, but a partially integrated approach has been achieved in a few recent studies (eg Rosenberg and Crosson 1991). All of these involved the linking of individual models. A general equilibrium modelling approach to environmental and economic interactions is necessary for assessments of the direct and indirect effects and benefits and costs of potential climate. Research to develop such models has become a priority in some regions.

### 3.3 Empirical analog studies

Observations of the interactions of climate and society in a region can be of value in anticipating future impacts. The most common method employed involves the transfer of information from a different time or place to an area of interest to serve as an analogy.

Three types of analogy can be identified: historical analogies, regional analogies of present climate and regional analogies of future climate. Historical analogies use information from the past as an analog of possible future conditions. Regional analogies of present climate refer to regions having a similar present-day climate to the study region, where the impacts of climate on society are judged also likely to be similar. If these conditions are fulfilled, then it may be possible to conduct assessments whereby a target case is compared with a control case, the target area experiencing abnormal weather but the control normal conditions.

Regional analogies of future climate work on the same principle as analogies for present-day climate, except that here the analyst attempts to identify regions having a climate today which is similar to that projected for the study region in the future. The analog region may thus provide indicators of how the landscape and human activities might change in the study region in the future.

### 3.4 Expert judgment

A useful method of obtaining a rapid assessment of the state of knowledge concerning the effects of climate on given exposure units is to solicit the judgment and opinions of experts in the field. Literature is reviewed, comparable studies identified, and experience and judgment used in applying all available information to the current problem. The use of expert judgment can also be formalised into a quantitative assessment method by classifying and then aggregating the responses of different experts to a range of questions requiring evaluation. Probability judgments from experts have been used to assess climatic change and its possible impacts (NDU 1978, 1980), but there have been problems of questionnaire design and delivery, selection of representative samples of experts, and the analysis of experts' responses (Stewart and Glantz 1985).

## 4 Testing the method

Following the selection of the assessment methods, it is important that these are thoroughly tested in preparation for the main evaluation tasks. There are many examples of studies where inadequate preparation has resulted in long delays in obtaining results. Three types of analysis may be useful in evaluating the methods: feasibility studies, data acquisition and compilation, and model testing.

### 4.1 Feasibility studies

Feasibility studies usually focus on a subset of the study region or sector to be assessed. Such case studies can provide information on the effectiveness of alternative approaches, of models, of data acquisition and monitoring, and of research collaboration.

### 4.2 Data acquisition and compilation

Data must be acquired both to describe the temporal and spatial patterns of climate change and their impacts and to develop, test and calibrate predictive models. Data collec-

tion may rely on existing information obtained and compiled from different sources, or require the acquisition of primary data, through survey methods, direct measurement or monitoring.

### 4.3 Model testing

The testing of predictive models is, arguably, the most critical stage of an impact assessment. Most studies rely almost exclusively on the use of models to estimate future impacts. Thus, it is crucial for the credibility of the research that model performance is tested rigorously. Standard procedures should be used to evaluate models, but these may need to be modified to accommodate climate change. Two main procedures are recommended: sensitivity analysis and validation. Sensitivity analysis evaluates the effects on model performance of altering its structure, parameter values, or values of its input variables. Extending these principles to climatic change requires that the climatic input variables to a model be altered systematically to represent the range of climatic conditions likely to occur in a region. Validation involves the comparison of model predictions with real world observations to test model performance. The validation procedures adopted depend to some extent on the type of model being tested. For example, the validity of a simple regression model of the relationship between temperature and grass yield would ideally be tested on data from additional years not used in the regression. Here, the success of the model is judged by its outputs, namely the ability to predict grass yield. Conversely, a simulation model might estimate grass yield based on basic growth processes, which are affected by climate, including temperature. Here, the different internal components of the model (such as plant development and water use) as well as predicted final yield each need to be compared with measurements.

An additional problem in considering climate change concerns the requirement in many models to extrapolate model relationships outside their normal range of application. Model validation and sensitivity analysis should serve to define the level of confidence that can be attached to such extrapolations.

## 5 Selection of the scenarios

Impacts are estimated as the differences between two states: environmental and socioeconomic conditions expected to exist over the period of analysis in the absence of climate change and those expected to exist with climate change. It is important to recognise that the environment, society and economy are not static. Environmental, societal

and economic change will continue, even in the absence of climate change. In order to estimate accurately the environmental and socioeconomic effects of climate change, it is necessary to separate them from unrelated, independent, environmental and socioeconomic changes occurring in the study area. Thus, it is necessary first to develop baselines that describe current climatological, environmental and socioeconomic conditions. Then it is necessary to project environmental and socioeconomic conditions over the study period in the absence of climate change. These baseline conditions are then compared, after impact projections, with environmental and socioeconomic conditions under climate change. Thus, development of baselines accurately representing current and projected conditions in the absence of climate change is a key and fundamental step in assessment.

### 5.1 Establishing the present situation

In order to provide reference points with which to compare future projections, three types of 'baseline' conditions need to be specified: the climatological, environmental and socioeconomic baselines.

#### 5.1.1 Climatological baseline

The climatological baseline is usually selected according to the following criteria:

- the representativeness of the present-day or recent average climate in the study region.
- the duration to be long enough to encompass a range of climatic variations, including a number of significant weather anomalies (eg a severe drought or an extremely cool season). Such events are of particular use as inputs to impact models, providing a means to evaluate the impacts of the extreme range of climatic variability experienced at the present day.
- the period covered to have adequate local climatological data available, in terms both of the number of different variables represented and of the geographical coverage of source stations.
- the date employed to be of sufficient quality for use in evaluating impacts.

A popular climatological baseline is a 30-year 'normal' period as defined by the World Meteorological Organization (WMO). The current standard WMO normal period is 1961-90. While it would be desirable to provide some consistency between impact studies by recommending this as an appropriate baseline period to select in future

assessments, there are also difficulties in doing so. Several points illustrate this.

First, this period coincides conveniently with the start of the projection period commonly employed in estimating future global climate (for example, the IPCC projections begin at 1990 (IPCC 1990a)). On the other hand, most GCMs providing regional estimates of climate are initialised using observed climatologies taken from earlier periods. Second, the availability of observed climatological data, particularly computer-coded daily data, varies considerably from country to country, thus influencing the practical selection of a baseline period. Third, it is often desirable to compare future impacts with the current rather than some past condition. However, while it can be justifiably assumed in some studies that present-day human or natural systems subject to possible future climate change are reasonably well adapted to the current climate, in other assessments this will not be the case. Finally, there is the problem that the more recent periods (particularly during the 1980s) may already include a significant global warming 'signal', although this signal is likely to vary considerably between regions and be absent from some.

Climatological data from the baseline period are used to describe the present climate of the study region and provide inputs for impact models. In the latter case, several methods are used. Some models produce estimates for periods of a year or less (eg crop growth models). These can generally use the original climatological station data for years within the baseline period.

Other models run over long periods of decades or centuries (eg soil erosion models). One option here is to select a long baseline period, but lack of data usually precludes this. An alternative is to use the baseline data on a repeating basis. For example, year 1 in a 30-year baseline could be used as years 1, 31, 61 and 91 of a 100-year simulation. One problem with this method is that chance trends or cycles in the baseline climate are then repeated in a manner that may be unrealistic over the long term.

To overcome some of the problems of data sparsity and of long-term cycles, some modelling studies now employ weather generators. These simulate daily weather at a site randomly, based on the statistical features of the observed climate. Once developed, they can produce time series of climatological data having the same statistical description as the baseline climate, but extending for as long a period as is required (see Hutchinson 1987).

#### 5.1.2 Environmental baseline

The environmental baseline refers to the present state of other, non-climatic environmental factors, that affect the

exposure unit. It can be defined in terms of fixed or variable quantities. A fixed baseline is often used to describe the average state of an environmental attribute at a particular point in time. Examples include: mean atmospheric concentration of carbon dioxide in a given year, mean soil pH at a site, or location of natural wetlands. A notable case is the mean sea-level, which is expected to rise as a result of future climate change. Furthermore, a fixed baseline is also required for specifying the 'control' in field experiments (eg of CO<sub>2</sub> effects on plant growth). A representation of variability in the baseline may be required for considering the spatial and temporal fluctuations of environmental factors and their interactions with climate. For example, in studies of the effects of ozone and climate on plant growth, it is important to have information both on the mean and on peak concentrations of ozone under present conditions.

### 5.1.3 Socioeconomic baseline

The socioeconomic baseline describes the present state of all the non-environmental factors that influence the exposure unit. The factors may be geographical (eg land use, communications), technological (eg pollution control, crop cultivation), managerial (eg forest rotation, fertiliser use), legislative (eg water use quotas, air quality standards), economic (eg commodity prices, labour costs), social (eg population, diet), or political (eg land set aside, land tenure). All of these are liable to change in the future, so it is important that baseline conditions of the most relevant factors are noted.

## 5.2 Time frame of projections

A critical consideration for conducting impact experiments is the time horizon over which estimates are to be made. Three elements influence the time horizon selected: the limits of predictability, the compatibility of projections and whether the assessment is continuous or considers discrete points in time.

### 5.2.1 Limits of predictability

The time horizon selected depends primarily on the goals of the assessment. However, there are obvious limits to the ability to project into the future. Climate projections, since they are a key element of climate impact studies, define the outer limit on impact projections. GCM estimates seldom extend beyond about 100 years, owing to the large uncertainties attached to such long-term projections and to

constraints on computational resources. This fixes an outer horizon at about 2100. Many climate projections are for a radiative forcing of the atmosphere equivalent to a doubling of CO<sub>2</sub> relative to pre-industrial levels. This could occur as early as 2020 (IPCC 1990a), which could be used as a mid-term projection horizon.

Of course, long time-scale projection periods may be wholly unrealistic for considering some impacts (eg in many economic assessments). On the other hand, if the projection period is too short, then the estimated changes in climate and their impacts may not be easily detectable, making it difficult to evaluate policy responses.

### 5.2.2 Compatibility of projections

It is important to ensure that future climate, environment and socioeconomic projections are mutually consistent over space and time. A common area of confusion concerns the relative timing of CO<sub>2</sub> increase and climate change. Thus, it should be noted that an equivalent 2xCO<sub>2</sub> atmosphere does not coincide in time with a 2xCO<sub>2</sub> atmosphere, and there are time lags in the climate response to both of these.

### 5.2.3 Point in time or continuous assessment

A distinction can be drawn between considering impacts at discrete points in time in the future and examining continuous or time-dependent impacts. The former are characteristic of many climate impact assessments based on 2xCO<sub>2</sub> scenarios. These consider impacts occurring at the time specified by the scenario climate (a time that is often not easy to define and which usually varies from place to place). They ignore any effects occurring during the interim period that might influence the final impacts. They also make it very difficult to assess rates of change and thus to evaluate adaptation strategies.

In contrast, transient climatic scenarios allow time-dependent phenomena and dynamic feedback mechanisms to be examined and socioeconomic adjustments to be considered. Nevertheless, in order to present results of impact studies based on transient scenarios, it is customary to select 'time slices' at key points in time during the projection period.

## 5.3 Projecting environmental trends in the absence of climate change

The development of a baseline describing conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. It is

highly probable that future changes in other environmental factors will occur even in the absence of climate change, which may be of importance for an exposure unit. Examples include deforestation, change in grazing pressure, changes in groundwater level and changes in air, water and soil pollution. Official projections may exist to describe trends in some of these (eg groundwater level), but for others it may be necessary to use expert judgment or simply to extrapolate past trends. Most factors are related to, and projections should be consistent with, trends in socioeconomic factors (see Section 5.4, below). GHG concentrations may also change, but these would usually be linked to climate (which is assumed unchanged here).

#### 5.4 Projecting socioeconomic trends in the absence of climate change

Global climate change is projected to occur over time periods that are relatively long in socioeconomic terms. Over that period it is certain that the economy and society will change, even in the absence of climate change. One of the most difficult aspects of establishing trends in socioeconomic conditions without climate change over the period of analysis is the forecasting of future demands on resources of interest. Simple extrapolation of historical trends without regard for changes in prices, technology or population, will often provide an inaccurate base against which to measure impacts.

Official projections exist for some of these changes, as they are required for planning purposes. These vary in their time horizon from several years (eg economic growth, unemployment), through decades (eg urbanisation, industrial development, agricultural production), to a century or longer (eg population). Reputable sources of such projections include the United Nations (eg United Nations 1991), Organization of Economic Cooperation and Development (eg OECD 1990), World Bank (eg World Bank 1990), International Monetary Fund and national governments.

#### 5.5 Projecting future climate

In order to conduct experiments to assess the impacts of climate change, it is first necessary to obtain a quantitative representation of the changes in climate themselves. No method yet exists of providing confident predictions of future climate. Instead, it is customary to specify a number of plausible future climates. These are referred to as 'climatic scenarios' and they are selected to provide climatic data that are spatially compatible, mutually

consistent, freely available or easily derived from, and suitable as inputs to impact models.

There are four basic types of scenario of future climate: historical instrumentally based scenarios, palaeoclimatic analog scenarios, arbitrary adjustments and scenarios from GCMs.

##### 5.5.1 Historical instrumentally based scenarios

An obvious source of climatological data for scenario development is past instrumental records. These are known to be spatially compatible and mutually consistent because they have actually been observed, and are available for the recent past over a reasonably dense network of land-based stations worldwide. Such scenarios can be based upon:

- *Historical-anomalies*, focusing on weather anomalies that can have significant short-term impacts (such as droughts, floods and cold spells). A change in future climate could mean a change in the frequency of such events. They are selected from the instrumental record as individual years or periods of years during which anomalous weather was observed (eg Parry and Carter 1988).
- *Historical-analogs*, which focus on past periods of global-scale warmth as potential analogs of a GHG-induced warmer world. They are usually developed on the basis of global-scale temperatures during past warm and cold periods, and consist of regional composites of the differences in climate between the two periods (eg Lough et al. 1983).
- *Historical-correlations*, which represent a variation of the analog approach, involving the estimation of linear relationships between the historical record of global surface air temperatures and records over the same period of local climatic variables. For a given variation in global temperature, it is then possible to estimate from these relationships expected variations in local climate (eg Vinnikov and Groisman 1979).
- *Circulation-patterns*, which are designed for cases where input data for impact models cannot be provided by conventional scenarios (eg wind fields for air pollution studies). The approach also uses linear relationships, this time between past global mean temperatures and regional atmospheric circulation patterns. Individual seasons are then identified in the historical record having circulation types resembling those found to be correlated with global warmth (eg Pitovranov 1988).

There is a number of difficulties associated with the use of instrumental scenarios:

- They are based on temperature changes during the past century that are much smaller than those possible in the future. Thus, they may not be applicable to conditions outside the range of past variations.
- The causes of past variations in global temperature may have been different from those responsible for a future GHG-induced change in temperature.
- The strength of the relationships between past changes in temperature and changes in other climatic variables is usually rather weak.
- The nature of the relationships between variables may be different in the future than those occurring in the past. It is also known that relationships established for the past can themselves vary, depending on the time period selected.

### 5.5.2 Palaeoclimatic analog scenarios

Palaeoclimatic scenarios are based on reconstructions of past climate from fossil evidence. Features of the past temperature and moisture regime in a region (usually at a seasonal time resolution) can often be inferred by assembling the different types of evidence. If absolute dating methods are available, and the spatial coverage of evidence is sufficient, maps can be constructed for particular time periods in the past.

In the context of future climatic warming, palaeoclimatic scenarios for warm periods in the past have been adopted in several climate impact assessment studies as analogs of possible future climate. They have been used extensively in Russia, where three periods have been selected to represent progressively warmer conditions in the northern hemisphere (Budyko 1989; IPCC 1990a): the Mid-Holocene (5–6000 years Before Present), when northern hemisphere temperatures are estimated to have been about 1°C warmer than today, the Last (Femian) Interglacial (125 000 BP) with temperatures about 2°C warmer than today, and the Pliocene (3–4 million BP) when temperatures were about 3–4°C warmer than today.

If the evidence upon which they are based is of good quality, palaeoclimatic scenarios can provide a reasonable representation of past climate, which is consistent in space and time. Moreover, they have an advantage over instrumental scenarios in that the level of global warmth is much greater than that experienced in the past century, and more closely analogous to the magnitude of warming expected during the next century.

There are some serious reservations, however, in using these reconstructions as scenarios of future climate:

- Boundary conditions of the climate system (eg sea level, ice volume, land cover) were not the same in

the past as they are today. Thus, even if the radiative forcing were the same, the climate response might differ in the future from that in the past.

- It is probable that some periods of past warmth resulted from different forcing factors than the future GHG forcing (eg orbital variations).
- There are large uncertainties about the quality of the palaeoclimatic reconstructions. None is geographically comprehensive, some may be biased in favour of climatic conditions that preserved the evidence upon which they are based, and the dating of material (especially in the more distant past) may not be precise.
- They represent the average conditions prevailing in the past. It is rare for them to yield concrete information on the variability of climate or frequency of extreme events.

### 5.5.3 Arbitrary adjustments

A simple method of specifying a future climate is to adjust the baseline climate in a systematic, though essentially arbitrary manner. Adjustments might include, for example, changes in mean annual temperature of  $\pm 1^\circ$ ,  $2^\circ$ ,  $3^\circ\text{C}$ ... etc, or changes in annual precipitation of  $\pm 5\%$ ,  $10\%$ ,  $15\%$  ... etc relative to the baseline climate. Adjustments can be made independently or in combination.

These types of adjustments are of use for testing the robustness of impact models, and for studying sensitivity to climatic variations (see Section 4.3). This is also the preferred method of altering climate and/or atmospheric composition when conducting climatic change experiments in the field or laboratory. Furthermore, the approach can be useful for expressing expert estimates of future climate, in the absence of more detailed projections.

Perhaps the most valuable function of arbitrary adjustments, however, is as a diagnostic tool to be used before conducting scenario studies. In this way information can be obtained on:

- *Thresholds or discontinuities of response* that might occur under a given magnitude or rate of change. These may represent levels of change above which the nature of the response alters (eg warming may promote plant growth, but very high temperatures cause heat stress), or responses which have a critical impact on the system (eg wind speeds above which structural damage may occur to buildings).
- *Tolerable climate change*, which refers to the magnitude or rate of climate change that a modelled system can tolerate without major disruptive effects (sometimes termed the 'critical load'). This type of measure is potentially of value for policy, as it can assist in

defining specific goals or targets for limiting future climate change.

One of the main drawbacks of the approach is that adjustments to combinations of variables are unlikely to be physically plausible or internally consistent. Thus, this approach should normally only be used for sensitivity analysis.

#### 5.5.4 Scenarios from GCMs

GCMs are the most sophisticated tools currently available for estimating the likely future effects of increasing GHG concentrations on climate. They simulate the major mechanisms affecting the global climate system according to the laws of physics, producing estimates of climatic variables for a regular network of grid points across the globe. Results from about ten GCMs have been reported to date (eg see IPCC 1990a).

GCMs are not yet sufficiently realistic to provide reliable predictions of climatic change at the regional level, and even at the global level model estimates are subject to considerable uncertainties. Thus, GCM outputs represent, at best, broad-scale sets of possible future climatic conditions and should *not* be regarded as predictions.

GCMs have been used to conduct two types of experiment for estimating future climate: *equilibrium-response* and *transient-forcing experiments*.

The majority of experiments have been conducted to evaluate the *equilibrium response* of the global climate to an abrupt increase (commonly, a doubling) of atmospheric concentrations of CO<sub>2</sub>. Clearly, such a step change in atmospheric composition is unrealistic, as increases in GHG concentrations (including CO<sub>2</sub>) are occurring continually and are unlikely to stabilise in the foreseeable future. Moreover, since different parts of the global climate system have different thermal inertias, they will approach equilibrium at different rates and may never approximate the composite equilibrium condition modelled in these simulations. This also results in difficulties in estimating the simultaneous effects of increasing CO<sub>2</sub> and climate change.

Recent work has focused on fashioning more realistic experiments with GCMs, specifically, simulations of the response of climate to a *transient forcing*. These simulations offer several advantages over equilibrium-response experiments. First, the specifications of the atmospheric perturbation are more realistic, involving a continuous (transient) change over time in GHG concentrations. Second, the representation of the oceans is more realistic, the most recent simulations coupling atmospheric models to dynamic ocean models. Finally, transient simulations

provide information on the *rate* as well as the magnitude of climate change, which is of considerable value for impact studies.

Information from GCMs is usually made available to impact analysts as surface or near-surface climatic variables for model grid boxes characteristically spaced at intervals of several hundred kilometres around the globe, and most commonly at a monthly time resolution. GCM projections of changes in climate under GHG-forcing relative to the control simulation are usually applied as adjustments (expressed as differences or ratios) to the observed baseline climate. Several techniques have been used to apply transient response outputs to the baseline climate (eg Croley 1990) and to provide data at a different time resolution from those obtained from GCMs (eg Bultot et al. 1988). One of the major problems faced in applying GCM projections to regional impact assessments is the coarse spatial scale of the estimates. Several methods have been adopted for developing regional GCM-based scenarios at sub-grid-scale, including assignment of the nearest grid box estimate (eg Croley 1990), objective interpolation (eg Parry and Carter 1988; Cohen 1991), statistical analysis of local climatic fields (eg Wilks 1988) and merging of several scenarios based on expert judgment (eg Pearman 1988) or averaging (eg Department of the Environment 1991).

There have been objections to the concept of using GCMs for developing climate change scenarios for regional impact studies, owing to uncertainties that prevent accurate regional-scale simulations. However, these scenarios are often beyond the design criteria of various facilities or resource systems, and it seems prudent to begin to test the sensitivities of these systems under various scenarios directly or indirectly based on GCM outputs to provide an indication of uncertainty in regional terms.

Many GCM simulations have been conducted in recent years, and it is not easy to choose suitable examples for use in impact assessments. In general, the more recent simulations are likely to be more reliable as they are based on recent knowledge, and they tend to be of a higher spatial resolution than earlier model runs. It is strongly recommended that recent reviews of GCMs be consulted before selection. The National Center of Atmospheric Research, Boulder, Colorado, USA, has been acting as a clearing house for GCM data from different modelling groups.

Finally, it has become common to use simple climate models rather than GCMs to estimate the effects on future global temperatures of alternative GHG emission scenarios (IPCC 1990a). Their attractiveness as policy tools makes it desirable to use these scenarios in impact studies. However, since only global estimates are provided they cannot be used directly in regional assessments. A method

of overcoming this problem makes use of GCM information in conjunction with the global estimates, whereby the GCM estimates of regional changes are scaled according to the ratio between the GCM estimate of global temperature change and that provided in the simple scenario (for example, for a doubling of CO<sub>2</sub>).

### 5.6 Projecting environmental trends with climate change

Projections must be made for each of the environmental variables or characteristics of interest in the study and included in the description of environmental trends in the absence of climate change. These projections are made using the climate projections and the biophysical models selected for the study (as described in Section 3.2.1). Because all changes in environmental conditions not due to climatic factors should already have been incorporated in the development of the environmental trends in the absence of climate change, the only changes in these trends to be incorporated here are those due solely to climate change. The two factors most commonly required in assessments are GHG concentrations and sea-level rise. Future changes in these are still under discussion, but the estimates reported by the IPCC may serve as a useful basis for constructing scenarios (IPCC 1990a). Other factors that are directly affected by climate (such as river flows, runoff, erosion) would probably require full impact assessments of their own, although some might be incorporated as 'automatic adjustments' in projections.

### 5.7 Projecting socioeconomic trends with climate change

The changes in environmental conditions that are attributable solely to climate change serve as inputs to the economic modelling that projects the changes in socioeconomic conditions due to climate change over the study period. All other changes in socioeconomic conditions over the period of analysis are attributable to non-climatic factors and should have been included in the estimation of socioeconomic changes in the absence of climate change.

It is not known how climate change might affect some important socioeconomic factors (eg population growth) and trends estimated in the absence of climate change would probably suffice. Other factors can be estimated, however (eg winter electricity demand in relation to future warming). Moreover, some human responses to climate change are predictable enough to be factored-in to future projections. These are often accounted for in model simulations as feedbacks or 'automatic adjustments' to

climate change (eg altering crop sowing dates to account for a shift in the timing of rainfall).

## 6 Assessment of impacts

Impacts are estimated as the differences over the study period between the environmental and socioeconomic conditions projected to exist without climate change and those that are projected with climate change. The impacts provide the basis for the assessment of impacts. Assessments may include:

- *Geographical analysis* of the impacts. Impacts vary over space, and this pattern of variation is of concern to policy makers operating at regional, national or international scales, because these spatial differences may have consequent policy and planning implications. The geographical depiction of climate change, presented as maps, is one method of describing impacts. Geographical information systems (GIS) may be used to depict patterns of climate change, evaluate the regional potential for different activities using simple indices, map changes in the pattern of potential induced by a given climate change, identify regions of particular sensitivity to climate change, and display the impact of climate on different activities within a given geographical region.
- *Compliance to standards*, which may provide a reference or an objective against which to measure the impacts of climate change. For example, the effect on water quality could be gauged by reference to current water quality standards.
- *Qualitative description*, which may be used to evaluate the impacts of climate change. The success of this method rests on the experience and interpretive skills of the analyst, especially the analyst's ability to consider all factors of importance and their interrelationships.
- *Costs and benefits*, which should be estimated quantitatively to the extent possible and discounted to net present value. This approach makes explicit the expectation that a change in resources and resource allocation due to climate change is likely to yield benefits as well as costs, and can also examine the 'waiting' costs or benefits of doing nothing to mitigate potential climate change. The choice of discount rate used to discount benefits and costs will vary from nation to nation, depending upon the economic and social circumstances of each. Some costs and benefits are difficult to assess in monetary terms, and will have to be considered in descriptive terms.

Finally, the assessment should also take into account the uncertainties resulting from choices of assumptions and modelling techniques, as well as incomplete knowledge of biophysical, social and economic processes and the long time horizons over which projections are to be made.

## 7 Evaluation of adjustments

Impact experiments are usually conducted to evaluate the effects of climate change on an exposure unit in the absence of any adjustments which might prevent, mitigate or exploit them, and are not already automatic or built in to future projections. It is these adjustments which form the basis of measures to cope with climate change. Two types are described here: feedbacks to climate and tested adjustments at the enterprise level. A third type, policy responses, is considered in Section 8.

### 7.1 Feedbacks to climate

The global climate system is influenced, in part, by interactions with the surface biosphere. To date, projections of future climate have assumed that the biosphere remains unchanged, but this is clearly unrealistic. As climate changes, so the pattern of vegetation and of other important organisms such as oceanic plankton, which feedback to climate, are likely to shift geographically. Impact models can identify these possible shifts, but they have not yet been linked effectively to climate models for simulating feedbacks to climate.

### 7.2 Tested adjustments at the enterprise level

Tested adjustments are experiments that can be conducted with impact models to evaluate alternative options for adjusting to climate change at the level of individual enterprises. To illustrate, a climatic scenario may indicate that the water requirements of a crop are no longer satisfied under a changed rainfall regime. In this case an adjustment that could be tested using a crop growth model might be the substitution of less demanding, short-season crop variety. Here, the adjustment is chosen by expert judgment, but evaluated using the model.

When analysing potential adjustments, it is useful to distinguish between two types: anticipatory and reactive. *Anticipatory adjustments* are put into place in prospect of impacts occurring (eg the breeding of drought resistant crop varieties). *Reactive adjustments* are implemented after impacts have occurred (eg the adoption of drought resistant varieties). In many cases, adjustment experiments can

assist in evaluating different options so that anticipatory, rather than reactive adjustments can be put in place.

Of course, not all adjustments can be tested. For some, an accurate evaluation may not be possible, and for others the required technology may not yet be available.

## 8 Consideration of policy options

Another method of responding to climatic change is through policy decisions. Apart from purely qualitative assessments, two methods of policy evaluation can be identified: policy simulation and policy exercises.

### 8.1 Policy simulation

In some assessments it is possible to simulate the effectiveness of alternative policy adjustments using impact models. Two types of policy response to climatic change are commonly simulated: mitigation and adaptive.

*Mitigation policies* refer to actions that attempt to prevent or to reduce changes in climate by altering the emission rates of GHGs. These effects can be estimated and the costs evaluated using a range of models. Impact assessments can assist in identifying targets for mitigation policy with respect to minimising the effects of climate change (see Section 5.5.3).

*Adaptive policies* recognise that climate changes will occur and that it is necessary to accommodate them in policy. For instance, the lifting of government subsidies on some food crops might be one policy method of offsetting overproduction due to a more favourable climate. Such a policy would rely on economic factors (ie reduced incentive) to bring about farm-level adjustments such as a switch to alternative crops giving a higher return.

### 8.2 Policy exercises

A second possible method of evaluating policy adjustments is policy exercises. These combine elements of a modelling approach with expert judgment, and were originally advocated as a means of improving the interaction between scientists and policy makers. Senior figures in government, industry and finance are encouraged to participate with senior scientists in 'exercises' (often based on the principles of gaming), whereby they are asked to judge appropriate policy responses to a number of given climatic scenarios. Their decisions are then evaluated using impact models (Brewer 1986; Parry et al. 1992).

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# B

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## Energy and industry-related issues

The work carried out under this task is discussed under the heading:

Energy; human settlement; transport and industrial sectors; human health; air quality; effects of ultraviolet-B radiation

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### III Energy; human settlement; transport and industrial sectors; human health; air quality; effects of ultraviolet-B radiation

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### III Energy; human settlement; transport and industrial sectors; human health; air quality; and effects of ultraviolet-B radiation

This supplementary report covers changes in knowledge of and insight into the impact of climate change on human settlement, energy, transport and industrial sectors, human health and air quality. The report also covers recent discoveries concerning the impacts of increased ultraviolet radiation from stratospheric ozone loss.

There have been many new studies reported in the last eighteen months. In human settlement, there has been more work on the implications of sea-level rise, and some important new findings have been made on the implications of soil shrinkage and swelling in the United Kingdom. In the energy area, there have been numerous studies both on demand and supply. New regional studies have also added depth to the understanding of potential variations in impacts. Apart from analysis of how industry might be affected by response strategies, however, there has been relatively little research on the direct impacts of climate change on industry or transport; the most important results come from a United Kingdom country study.

Knowledge of climate change on human health has been extended and confirmed with greater understanding of potential increases in disease during 'heat wave' and potential shifts in disease vector habitats with global warming, particularly in New Zealand and Australia. Diseases such as malaria, Chagas disease (trypanosomiasis), lymphatic filariasis, schistosomiasis, leishmaniasis, onchocerciasis (river blindness), dengue fever, and Australian and Japanese encephalitis could increase or be reintroduced in many countries as a consequence of global warming (WMO 1990). There is greater understanding of the mechanisms of the effect of temperature on air pollutants. Finally, recent studies have linked ultraviolet-B radiation (UV-B) to additional effects that had not been proposed previously. Immunosuppression has been demonstrated in peoples regardless of pigmentation, and new types of damage to the eye, deformations of the anterior lens and presbyopia, have also been linked to UV-B.

Strong impacts on marine organisms from conditions stimulating reduced ozone (ie enhanced UV-B) have been demonstrated in the laboratory. In the Antarctic, enhanced UV-B has been linked to a reduction of primary production rates of 6% to 12% from decreased photosynthesis. Studies were also undertaken on the biochemical and photochemical characterisation of representative species of the bacterioplankton in the southernmost region of Argentina (Ushuaia, Beagle Channel, Lapataia and three lakes in Tierra del Fuego—Orce (1990)) New laboratory studies have expanded knowledge about which terrestrial plants are sensitive to increased UV-B.

Regional studies, including country impact studies of New Zealand (1990), the United Kingdom (1991), Mexico (1990) and Russia (1991), as well as a number of country studies prepared for the Asian-Pacific Seminar on Climate Change (Nagoya 1991) and a United States Department of Energy study covering four states in the interior of the US (MINK) have been released since the last IPCC WGII report. A summary of the UNEP impacts report covering five countries in the developing world (Brazil, Thailand, Malaysia, Indonesia, and Vietnam) is available now, and the full report should be available shortly.

#### 1 Energy

Energy demands in lower latitudes are expected to increase, particularly in developing countries, as access to and need for air-conditioning grows. Higher latitude industrial countries can expect slight decreases in energy demand from decreased space heating. However, the overall cost of energy in some countries may rise considerably because of increased production costs as a result of climate change and permafrost thaw. Projections for Northern Russia indicate an increase of 20% in the calculated price of natural gas and oil resulting from a 2°C warming, although hydro-electric production could grow by 7–10% between 2000–2020 owing to increased river run-off (Yakovlev 1991). Biomass production, upon which developing countries depend for much of their energy needs, could be altered by climate change; better regional forecasts are needed to assess impacts on specific regions.

#### 1.2 Energy consumption

Space heating/cooling of buildings is one of the most climate-sensitive uses of energy, especially the use of electricity for residential and commercial air-conditioning and electricity plus other fuels for space heating. Two key questions are, first, the potential increases in the ownership and use of air-conditioning and how climate change might influence them and, second, the potential impact of climate change on availability of traditional biomass fuels and consequent changes in energy use. Studies in Argentina on the comfort requirements of local representative biotypes suggest a reduction in energy requirements for air-conditioning could result. Although usually smaller in total magnitude of energy demand, the use of electricity and fuels for irrigation pumping and use of fuels for drying of

agricultural crops also can be significant weather-sensitive demands in some regions. Climate change has negligible direct effect on vehicle performance; however, transportation is sensitive to immediate impacts due to weather and may be indirectly sensitive to gradual shifts in activities in response to climate change and to greenhouse gas response strategies. Substantial impacts on traditional uses of energy in developing countries, such as cooking, are likely in response to shortages of supply.

### *1.3 Energy supply systems*

The main impact on supply discussed earlier was the potential for changes in hydro-electric power generation due to changes in water runoff. There are relatively few studies of most other potential impacts on supply.

The lifetimes of many energy supply facilities and of energy-using systems are comparable to or shorter than the time-scale for substantial changes in climate (UKDOE 1991). Changes in demand due to climate change appear to be small compared with potential changes due to other factors, such as economic and population growth, lifestyle and technology changes etc. Hence, adjustments in the energy supply system and in energy-using equipment to accommodate climate changes often can be made in the course of normal replacement. Adjustments in supply system planning to accommodate climate change should be feasible; costs will usually be small-to-moderate if the impacts of climate change and other determinants of demand are anticipated (Linder et al. 1989). However, the overall cost of energy in some countries may rise considerably due to increased production costs as a result of climate change and permafrost thaw. Projections for Northern Russia indicate an increase of 20% in the calculated price of natural gas and oil resulting from a 2°C warming (Yakovlev 1991).

Climate change could affect steam and nuclear electric power plants. They are vulnerable to curtailments of water supply for cooling and are moderately sensitive to increases in wet-bulb air temperature or water temperature, depending on the type of cooling system. Anticipation of climate extremes when designing plants can avoid many of the problems, but water supply during extreme drought depends on the overall water management situation in each basin. An example of potential problems with both steam electric and hydro-electric systems during drought was the event in the summer of 1988 in the eastern US. Water runoff shortages caused decreases in hydro-power and in available steam electric power coincident with increased air conditioning loads. However, the electric system was able to handle the situation without curtailment of power.

Some renewable energy systems such as solar, wind energy, and biomass are directly sensitive to climate change. Central solar thermal electric systems and many geothermal systems are similar to steam electric plants in terms of cooling requirements, although there are differences in sensitivity due to their steam temperature. Biomass energy systems are similar to agriculture and forestry in sensitivity to climate change, except for differences in management practices. Intensively managed biomass systems may be able adapt to changes subject to availability of water resources.

### *1.4 Developing countries*

Developing countries tend to have different mixes of energy technologies and are often at different stages of development of their energy-using and supply systems than developed countries. Since drought conditions tend to diminish both hydro and traditional biomass sources simultaneously, countries with a relatively high dependence on those sources are more vulnerable. Africa, non-OECD Asia and Latin America are particularly high in dependence on biomass energy, ranging from as high as 100% in one country and above 90% in a number of African and Asian countries. Latin America and non-OECD Asia also are particularly high in dependence on hydro-power. Semi-arid countries usually are most vulnerable to natural fluctuations in precipitation, even without global climate change. Tropical developing countries represent a potentially large source of increased demand for electricity for air-conditioning. Demand may grow both with improved economic conditions and with higher temperatures.

### *1.5 Regional studies*

Since the first IPCC assessment of the impact of climate change on the energy sector, several regional or utility-specific studies have been published. These studies examine changes in energy supply and demand simultaneously for the specific regional energy scheme. The methods and magnitude of impact vary, but together these studies serve to illustrate the importance of specific regional impact studies, especially for long-range plans which may already be in progress. Regional studies, the results of which are discussed below, are from the US, Finland, New Zealand, Great Britain, Japan and the former USSR.

Climate sensitivity in the energy sector and in energy use varies greatly from region to region. Hydro-electric power is sensitive to temperature and precipitation; in some regions, because of evaporative losses, even increased precipitation does not lead to increased streamflow.

Thermal plants are moderately sensitive to increases in air and water temperature, but water supply problems can lead to power interruption. Areas in which seasonal demand is highest in the winter may have significantly lowered total annual energy needs. In contrast, regions with high or increasing air-conditioning demand may have a significant increase in summer daily peaking, with substantial costs for additional peaking capacity, but only moderate additional energy costs.

## 2 Human settlement

Among the most significant of all the potential impacts of climate change are the possible effects on human settlements, a broad term meant to encompass a) housing or shelter, b) the surrounding village, neighbourhood or relevant social unit in which individuals live, c) the supporting physical infrastructure (eg water services, communication links, transportation) and d) social and cultural services (eg health services, education, police protection, recreational services, parks and so on).

The Missouri-Iowa-Nebraska-Kansas (USDOE 1991) study sponsored by the US Department of Energy uses a new and sophisticated methodology. It incorporates historical analogies from a period in which the weather was close to projected changes in climate, analysis of contemporary systems such as hydrological regimes and the networks that comprise the economy of the MINK area, and impositions of expected climate change both on the present natural and economic situation and on what the area will be like in 2030. Although the study is thorough throughout, its strength is in a study of the interconnections and relative importance of various parts of the economy on a small scale, using the US Forest Service's IMPLAN input-output model. This allows for a very complex understanding of the impacts that changes in sectors sensitive to climate would have on the larger economy of this highly developed region.

The projected economic impact of climate change (corresponding to an increase of 100 parts per million in CO<sub>2</sub>, or a 0.65–0.9°C rise by 2030) on this agriculturally oriented part of the United States, according to the authors of this study, would be negligible except in a worst-case scenario. They conclude that agriculture would be negatively affected, but also that adjustments for on-farm adaptations and CO<sub>2</sub> enrichment of crops drop the impact below the level required to affect significantly the economy as a whole. The relative importance of manufacturing—even in this relatively specialised agricultural area—would, in effect, cushion the economy at large from possible damage. It is worth noting, however, that the temperature rise used in this analysis is below that which the IPCC

Working Group I is predicting for the earth as a whole (1°C), and that all models are predicting greater warming in the interior of continents and in decades subsequent to the 2030s.

It is likely that consequential impacts of climate change can be more reliably projected on developing societies than on highly industrialised nations; there is abundant evidence that the former are already tackling formidable problems caused by climatic variability and human actions. Tropical cyclones such as the one that ravaged Bangladesh in May 1991, the recent flood in south China that left over a million homeless, and the drought-induced famine that has plagued Sudano-Sahelian Africa over the past decade (Oguntoyinbo 1991) are all manifestations of the extraordinary present vulnerability of the populations of developing countries to extreme climatic events.

The economic and social viability of such island nations as Tuvalu, Tokelau, Kiribati, the Marshall Islands and the Maldives could be imperilled by a rise in the mid range of current sea-level rise projections (Roy and Connell 1991). A rise of one metre (at the upper range of sea-level rise projections for 2100) could also displace 20–25 million people in Bangladesh (Asaduzzaman 1991) and flood delta regions in China, Egypt and India (Tickell 1989). Sea-level rise appears to be the most dangerous potential effect of global climate change on human settlement.

The study of Mexico (Liverman 1991) and the discussion of Brazil in the executive summary of the five-country UN Environment program study (Parry 1991) both emphasise that *vulnerability* to future climate change can in part be extrapolated from contemporary ecological and social reactions to climatic *variability*.

In Mexico, intense local conflicts over water rights between different types of farmers, and also with urban-dwellers, combined with large regional losses of crops to drought, illustrate the vulnerability of Mexico to changes in precipitation. Disasters can also point out this vulnerability; in Brazil, intense rainfall in Rio de Janeiro in February 1988 caused 300 deaths and \$1000 million in economic losses. A very high (evidently too high) density of population and economic activity was largely responsible in this case.

In Northeast Brazil, where losses from drought are associated with the problem of poverty, a study found that 'social and economic consequences of droughts are explained by local factors such as social organisation, education and technological level as much as by weather variation' (Parry 1991 p.9). Thus, as shown in infant mortality statistics, government action in the form of public works projects may be able to offset the malnutrition caused by drought for the first few years, but as the

drought continues and deepens, children die more frequently. The study concludes that more frequent extreme drought would greatly increase the impact on the rural poor (Parry 1991). Drought is also not necessarily wholly derived from factors external to the area in question. In Northeast Brazil, for example, it is in part attributable to extensive deforestation (Parry 1991).

The Brazilian and Mexican studies found that human activity both reveals and occasionally even causes vulnerability to climate variation, which can be indicative of vulnerability to climate change. Vulnerability, socioeconomic or biophysical, can indicate areas or populations where ameliorative or preventive action can be of use now as well as in possible future climates, especially where both the people and the place they live in are vulnerable to climate change.

Various studies have highlighted the potential significance of changes in the El Niño/Southern Oscillation phenomenon (ENSO) that might accompany global warming. It is estimated that the El Niño of 1982–83 caused losses of \$US3 billion in the Southeast Pacific owing to disruptions in agriculture, destruction of infrastructure, and declines in fisheries production (Sotelo 1991). In Vietnam, highly productive fisheries (at the edge of upwelling and downwelling regions) have shifted during El Niño events and, as a result, overall production has declined sharply (Parry 1991). ENSO amplifies climate variability, imposes a specific temporal pattern to drought and heavy rainfall periods, and allows some predictability of these variations in Southeast Asia. If this variability is enhanced under a changed climate, then sustainable development could be made much more difficult (Nicholls 1991). Changes in atmospheric circulation that may occur under conditions of global warming could alter, by changing the connections between low and middle latitudes, the impacts of ENSO, even if the phenomenon itself remains unchanged (Nicholls 1991). At this point, however, the direction and potential magnitude of changes in ENSO under conditions of climate change is uncertain, so it is impossible to make projections of likely impacts of changes in ENSO.

Drought has a differential impact on farmers, depending on their economic and social circumstances. In Mexico, it has had a different impact on different segments and sociopolitical types of farmers. Ninety per cent of losses from natural hazards are from drought in Mexico; *Ejidat* or communally held farms, however, have consistently suffered more losses (to a maximum of twice as much in 1970) from drought than privately owned farms. This is partly explainable by the 'biophysical marginality' of these lands, but also by a lack of access to irrigation, credit and other resources. Liverman (1991) goes on to conclude that land reform and level of agricultural modernisation affect the degree of vulnerability to climate

variation. These factors would also potentially affect vulnerability to global warming.

Climate change could alter the in-country urban to rural population balance. Parry (1991) states that reductions in rubber production (extrapolated from the GISS 2xCO<sub>2</sub> climate scenario) in Malaysia could increase the current tendency of rubber smallholders to sell out to larger estates and move to cities. A similar urban exodus was caused in Bangladesh by massive floods from 1974–81; fully 1% of the population shifted to the cities as a result of those disasters (Asaduzzaman 1991). Sea-level rise and continued subsidence of the delta is expected to increase flooding in Bangladesh, so this type of shift can be expected to continue.

Sea-level rise along with flooding and drought may be the source of a potential *international* environmental refugee problem, with many persons fleeing their homelands to other countries. Such a refugee problem has become acute in the Horn of Africa because of a combination of drought, famine and civil war and it is likely that sea-level rise will become a force for inter-country movement. New Zealand is already considering the possibility of taking in refugees from South Pacific island populations who may face the loss of their homelands (New Zealand 1990).

Along with the prospect of a new immigration, New Zealand has also identified a potentially severe cultural impact resulting from possible displacement of the Maori. The Maori do not recognise themselves as separate from their land, and many live in low-lying areas prone to floods and possibly vulnerable to sea-level rise.

### 3 Industry and transport

Recent impact studies covering transportation only involve developed countries such as Canada, New Zealand and the US. It should be noted that the impact of transportation on climate change is very great (UK 1991) and that policies implemented to alter climate change may change the world transportation network a great deal.

Generally higher temperatures would mean lower maintenance costs, especially with a reduction in freeze-thaw cycles and if climate change produces less snow (Parry and Read 1988). The annual costs of winter maintenance in the UK is now about £120 million (Perry and Symons 1991), but new technologies in ice detection and in forecasting minimum road temperature could decrease these costs. Salt could be reduced by 20%, resulting in savings in direct costs as well as from reduced damage to cars, trucks, and road infrastructure. Savings to the Great Lakes region are estimated at \$4.5 million annually in snow and ice control costs and \$700 000 a year in de-

creased frost damage to roads and bridges (Jones and Frith 1989).

A decline in weather-related accidents could be expected, although the relationship of accidents to weather is not linear. Of fatal accidents in New Zealand, 3.8% can be attributed to weather (Steiner 1990), and in the UK, £300 million (out of five billion) of damage from road accidents could be attributed to weather (Palutikof 1991, 1990). The severity and frequency of accidents is measurably sensitive to weather, and changes in climate could possibly change human and economic losses.

In the Great Lakes system and on inland waterways in the UK, lower water levels from increased evaporation would lead to lower lake levels and a decreased cargo capacity, 13% in the Great Lakes under the GISS scenario (McBoyle and Wall, in press). Arctic shipping, however, would have a significantly lengthened season.

Water-based industries will receive the most direct impacts from climate change. Industries needing water, such as paper making, food processing, and power generation could be affected by changes in supplies in a hydrologically different world. The US MINK study reports that industrial production would be reduced by 'a few billion dollars—maybe 2 or 3...' (VI, p. 26, USDOE 1991). This reduction would not however have a significant impact on industry or the economy as whole unless agricultural production dropped by more than 10%.

Since a large proportion of industry is established near coasts and waterways for easier access to transportation, cooling, energy, and waste removal, it could be endangered by sea-level rise. In the UK, 40% of the industrial sector is located in coastal and estuarine areas. The value of property protected by the Thames barrier alone is estimated at £10–20 billion (UK 1991). The threat is common to both industrialised and developing countries alike as civilisation has historically developed near coastal areas and waterways. Oguntoyinbo (1991) warns that the transportation, housing and industrial infrastructures of many West and Central African coastal cities could be at risk from sea-level rise.

A study of climate's present and future influence on the economy of Europe enumerates many possible implications of changes in climate and ultra-violet radiation for the construction and insurance industries. Design parameters for construction are currently based on historical climate conditions, particularly the extreme values of temperatures, wind speed, groundwater levels and rainfall. Some of these values will change with climate change; others are expected to, although the magnitude and direction of change are still in doubt. The study recommends that future design take account of possible changes in climate from greenhouse gas forcing. Another parameter that will change in the future is the future level of ultraviolet radiation (from

destruction of stratospheric ozone—see Section 6). Synthetic materials already sensitive to UV-B such as plastic polymers (used in paints, window frames, and roof coverings) could degrade more quickly with enhanced UV-B.

In the insurance industry, risk estimates in areas such as damage from storms have been based on historic loss statistics. This may not be as viable an approach in the future, especially given that damage from extreme events tends to rise rapidly with small increases in, for instance, maximum wind speed. Changing climatic baselines could alter the probability of such high-loss events; the authors of the study suspect in fact that human activity already has.

#### 4 Health

Global warming may indirectly affect morbidity, mortality and human health. For example, in temperate regions, mortality for pneumonia and bronchitis, and cardiovascular, cerebrovascular and heart diseases achieve a winter maximum and a summer minimum (Momiya and Katayama 1972). Mortality of infectious diseases other than pneumonia and bronchitis is also seasonal, but increases both in winter and in summer (Ando 1991). As a result of global warming, the mortality rates may be reduced in winter and increased in summer (Iriki and Tanaka 1987).

Global warming should affect human hazards such as parasites and pathogens, as well as those deriving from chemical pollutants. It could also affect human health by producing changes in air and water quality (Pearman 1988; Ewan 1990; Smith 1991; Breslav et al. 1991). Sea-level rise and acceleration of drought conditions could produce large numbers of environmental refugees with concomitant health problems.

Health problems may increase in cities as the already sizeable 'heat island' effect, which has been proven to raise temperatures in cities, is added to raised temperatures associated with global warming (Sugandhy 1991).

Estimating the pathophysiological mechanisms of the adverse effects of heat stress on human health requires experimental studies using model animals. Heat stress in laboratory animals significantly induces lipid peroxidation in the liver (Ando 1991). Heat stress has significant physiological and epidemiological impacts, and increased heat stress from climate change could lead to increased mortality in certain countries. The degree of acclimatisation (adaptation) to rising temperatures is expected to be extremely important in determining the extent of expected increases in mortality (Kalkstein 1989).

Multi-year observations of the runoff and chemistry of 168 Russian rivers show that a runoff reduction of

30–50 mm (that would result from a temperature increase of 1.2°C) would increase river pollution. The concentrations of a number of pollutants in river water would exceed national water quality standards in a territory of over 1.2 million km<sup>2</sup>. This would render the water unsuitable, without pre-treatment, as a potable water supply for human settlement (Breslav, Boltneva, and Nazarov 1991). The solubility of many pollutants in water is also expected to rise with increased temperature.

Global warming may modify the incidence and range of vector-borne diseases. If global warming changes rainfall and temperature patterns, the seasonal and geographical abundance of the major vector species could change. Since some vector-borne diseases are well known to show apparent seasonal changes, the diseases seem to be very sensitive to climate, and thus could be sensitive to global warming. Diseases such as malaria, Chagas disease (trypanosomiasis) schistosomiasis, lymphatic filariasis, onchocerciasis (river blindness) leishmaniases, dengue fever, yellow fever, Japanese encephalitis (WHO 1990), and Australian encephalitis (Ewan 1990) could potentially increase or be reintroduced in many countries as a consequence of global warming.

More specifically, a recent New Zealand study concludes that global warming could increase the possibility that many medically important pest species currently not present in New Zealand could become established there. One species, the dengue-bearing *Aedes albopictus*, has recently arrived in Fiji, and is poised to enter New Zealand. The islands of Tokelau are also at risk from the pest, with sea-level rise potentially creating more brackish water in which it could breed. *Aedes aegypti*, which also carries dengue and dengue haemorrhagic fever, has only been kept out of New Zealand by a few degrees of cold, and warming could thus easily change this situation. The mosquito that is most important medically in New Zealand (*Culex quinquefasciatus*) could also expand its range with increased temperature (New Zealand 1990).

## 5 Ultraviolet radiation and health

One supposition about impacts of UV-B on health that has been confirmed is that UV-B induces immunosuppression in humans. This was found to affect humans regardless of pigmentation, and could lead to greater incidence or severity of infectious diseases including (but not limited to) the viruses involved in herpes, papilloma, and acquired immunodeficiency disease. Previous speculation had been that peoples with dark pigmentation might not be at risk, but this new discovery indicates that all the world's population is at risk from UV-B induced immunosuppression (UNEP 1991).

Although UV had been associated with damage to the lens, retina and cornea, including the formation of two kinds of cataracts, two new conditions have been related to UV exposure. These are presbyopia, often called age-related near-sightedness, and deformations of the anterior lens capsule (UNEP 1991).

Exposure to UV-B is known to be associated with increased skin cancers ranging from basal cell and squamous cell carcinomas (BCC and SCC) to more dangerous melanomas. Research within the last two years has confirmed this further, but has slightly reduced projections of incidence from a decrease in ozone. A change in the radiation amplification factor for non-melanoma skin cancers has reduced projections of incidence increase from 2.7% (BCC) and 4.6% (SCC) per 1% ozone reduction to 2.0% and 3.5%, respectively (de Gruijl et al. to be published). This has been supported by Moan (1991) in estimations of SCC and BCC incidence in the Norwegian population. The most up-to-date estimate of skin cancers caused by decreased ozone (a 10% decrease lasting two to four decades) after three to four decades is 300 000 additional cases of non-melanoma cancer and 4500 additional cases of melanoma (UNEP 1991). Recent reports also indicate that salivary gland cancer (which is a non-skin cancer) may be associated with UV-B exposure (Spitz 1988, 1990).

## 6 Air quality

Global warming would accelerate the photochemical reaction rates among chemical pollutants in the atmosphere, increasing oxidants in many urban areas (Hatakeyama et al. 1991). In the summer, high concentrations of oxidants are already observed in the major metropolitan area. Predicted global warming may increase the ozone concentration in this and other metropolitan areas and increase the extent of this pollution as well (Ando 1991).

Climate changes could be a major factor on long-term trends in acid deposition, air pollution in urban areas, and levels of radon emitted from soils (Nazarov 1991).

The main pollutants derived from photochemical reactions are ozone and peroxyacetyl nitrates. There is a great deal of evidence associating these photochemical oxidants with acute effects on human health. Gas-particle partitioning coefficients and gas-phase reaction rates with RO<sub>2</sub>, OH, and O<sub>3</sub> are temperature dependent (Pankow and Bidleman 1991; Atkinson 1990).

Biogenic emission of NO and VOC such as isoprene would be increased with the increase of air temperature (Williams et al. 1987; Junti and Atkinson 1990; De Leeun et al. 1990). An increase of 5°C could lead to an almost

50% increase in the total source strength of CH<sub>4</sub> (Hameed and Cess 1983). A 2°C increase in temperature could be associated with a 10–30% increase in tropospheric H<sub>2</sub>O levels, implying a few per cent increase in OH and other HO<sub>x</sub> family members (Thompson et al. 1989).

The RTM-III model was run using an increased temperature scenario (a uniform 4°C with an increase in water vapour concentration assuming constant specific humidity). Peak daily ozone concentrations in the warmer model increased by 3% to 20% (mean increase of 9%). In the midwestern and southeastern United States, the changes in ozone ranged from -2.4% to 8.0%, with a mean value of 3.4% (Morris et al. 1989). The model suggests that approximately three times as many people in central California and 60% more people in the midwestern/southeastern modelling domain would be exposed to ozone concentrations in excess of US air quality standards as a result of the 4°C increase.

All the other model calculations lead to similar tendencies of increase in urban oxidant formation with the increase in air temperature (Dodge 1989; Penner et al. 1989). A decrease in column ozone of 20% would lead to an OH increase of roughly 15% over continental areas (Thompson et al. 1989; Liu and Trainer 1988). The concentrations of HNO<sub>3</sub>, PAN and H<sub>2</sub>O<sub>2</sub> would be increased for reduction in overhead ozone (Frank et al. 1991).

However, recent information indicates that much of the warming would occur at night. Generally that will not affect photochemical oxidation because of the absence of sunlight during that period. Moreover, warming may cause both increased cloudiness and more instances of rainfall: both factors would tend to reduce oxidation and encourage cleansing of the atmosphere. Thus, the net effect on the ambient air quality due to climate change is uncertain in both direction and magnitude.

## 7 Effects of ultraviolet-B radiation

### 7.1 General results

The effects of UV-B radiation on approximately 300 species and varieties of plants have now been studied. Of those studied, nearly one-half showed physiological damage and/or growth in response to UV-B radiation (Teramura and Sullivan 1991). A summary of studies conducted on soybean shows that 26 of 41 cultivars tested were sensitive (growth reductions exceeding 5%) to UV-B radiation in field or greenhouse studies (Teramura and Sullivan 1991).

It is now widely known that plants grown in growth chambers appear to be more sensitive to a given UV dose

than field-grown plants. The basis for this difference in sensitivity comes from the fact that in artificial environments only a single factor is manipulated; all other factors are either kept constant or are optimised for growth. Such single factor stresses are rarely experienced by plants outdoors (Teramura and Sullivan 1991).

A general response to drought, nutrient limitations and high irradiance (visible and UV) is the accumulation of flavonoids in epidermal tissues. These compounds absorb strongly in the UV-A and UV-B spectra and their accumulation in the epidermis has been shown to reduce epidermal transmittance of UV. It has now been established that the synthesis of several of the key enzymes in the flavonoid biosynthetic pathway are induced by UV-B (Teramura and Sullivan 1991).

A study of the comparative and cumulative effects of UV-B on wheat, rice and soybean seed yields and total biomass revealed that UV-B in combination with CO<sub>2</sub> eliminated the latter's enrichment effects in either seed yield or biomass for wheat and rice, but yields and biomass increased or were maintained in soybeans (Teramura 1990). Solar radiation bleaches cellular pigments of freshwater and marine phytoplankton and also impairs motility and photomovement of the plankton. These effects seem to be caused by solar UV-B (Eggersdorfer and Hader 1991; Hader and Hader 1989a, b; 1990a, b; Hader and Worrest 1991). In the paraflagellar body, UV-B radiation has been found to affect the proteins that carry the photoreceptor chromophores, flavins, and pterins. In addition, the chromophores are affected by the radiation.

Recent measurements in Antarctic waters have indicated a reduction in photosynthesis rates of 6% to 12% for total water column productivity at times and locations when increased UV-B was experienced (Smith et al. 1992). The photosynthetic pigments are affected and consequently the production of energy and reduction equivalents decreases, which in turn hampers CO<sub>2</sub> incorporation in organic material (Hader and Worrest 1991). UV-B has been found to have an effect as far down in the oceans as 37 metres (UNEP 1991).

Marine invertebrates differ greatly in their sensitivity to UV-B radiation. Small crustacean and larval shrimp are particularly sensitive to UV-B radiation. There is evidence that a decrease in column ozone abundance could diminish the near-surface season of invertebrate zooplankton populations. For some zooplankton, the time spent at or near the surface is critical for food gathering and breeding (Hader and Worrest 1991).

The marine phytoplankton communities represent by far the largest ecosystem on earth. Therefore, even a small percentage decrease in population would result in enormous losses in the biomass productivity of the ocean,

which would have dramatic effects both for the intricate ecosystem itself and for humans, who depend on this system in many ways (Hader et al. 1989).

There may be considerable differences in sensitivity to UV-B radiation between phytoplankton species (Kelly 1986; U.S. EPA 1987). Increased UV may lead to a pronounced shift in the species composition of the primary producers as well as of the consumers. Indirect effects may also occur in the form of altered patterns of predation, competition, diversity, and trophic dynamics if species resistant to UV-B were to replace sensitive species (Hader 1991).

Any decrease in the phytoplankton populations will decrease the sink capacity for atmospheric CO<sub>2</sub>. A population decrease of 10% would equal the net CO<sub>2</sub> increase due to fossil fuel burning. This is not yet accounted for by the current climate change models (Hader 1991).

### 7.2 Determination of sensitivities

Given a 16% ozone decrease over temperate pelagic waters, UV-B radiation levels at a depth of 1 meter would reach a lethal (50% mortality) cumulative radiation dose in fewer than 5 summer days for about half the zooplankton species examined. Perhaps even more important, the threshold levels of UV-B exposure would occur earlier in the year than has been the case, a time when these species are normally found near the surface (Damkaer et al. 1981; Dey et al. 1988).

On the North American Pacific coastal shelf, anchovy larvae are restricted to the upper 0.5 metres, and therefore a 16% ozone reduction could lead to large increases in larval mortality (Hunter et al. 1982). Experiments have shown that larvae 2, 4, and 12 days old would have 50, 82, and 100% mortality (Hader and Worrest 1991).

For the sensitive soybean cultivar, a 25% ozone reduction reduced overall yield by 19–25% during four of the six years. In contrast, yield increased from 5 to 22% in five of the six years for the UV-B resistant cultivar (Teramura and Sullivan 1991). After three years of supplemental irradiation of UV-B simulated those that would be anticipated with stratospheric ozone reductions of 16% and 25%, plant biomass was reduced by 12% to 20% at the highest simulated ozone depletion (Sullivan and Teramura 1991).

### 7.3 Study tasks for the near future in aquatic ecosystems

The molecular mechanisms for UV-B damage need to be determined for many zoo- and phytoplankton species,

especially those that are ecologically important. The question remains whether the gene pool within plankton species is variable enough to adapt during the relatively gradual changes anticipated for UV-B radiation exposure.

The combined effects of direct (larval mortality) and indirect (food web) losses cannot as yet be predicted, nor have assessments been made of adaptive strategies or genetic selections that could minimise population or ecosystem effects.

The problems of extrapolating laboratory findings to the open sea, and the nearly complete absence of data of the long-term effects and ecosystem responses make it difficult to assess the possible long-term impacts of increased UV radiation.

The interaction between UV-B dose and microclimate variation needs further evaluation. Studies extending over several growing seasons and an evaluation of the metabolic or energetic costs of producing and maintaining high flavonoid concentration will be necessary to determine the effects of increasing solar UV-B radiation on overall tree productivity.

UV-tolerant plants do possess various types of UV-protective and repair processes, which suggests that increased UV resistance in crops might be achieved via breeding programs. But we currently lack information on the genetic basis and heritability of UV resistance to estimate the feasibility of such crop improvement programs.

We know very little about potential indirect effects of UV-B radiation changes on competitive ability or resistance to insects and pathogens.

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## **Agriculture and forestry-related issues**

The work carried out under this task is discussed under the headings of:

Agriculture and forestry

Natural terrestrial ecosystems

Hydrology and water resources

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## **IV Agriculture and forestry**

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# IV Agriculture and forestry

## I Agriculture

### Progress since 1990

Since the publication of the first IPCC Impacts Assessment, progress in the study of agricultural impacts of climate change has continued on many fronts. In this update, we have adopted the structure of the original IPCC report on agriculture and forestry and for each section of the original report, we identify first, what, if any, new work has been done and second, whether this new work leads to any different conclusions from the 1990 report. New sections are added where necessary.

### 1 Climatic scenarios

While assumptions about climatic scenarios have not changed for the purposes of the ongoing IPCC assessment, it is important to note that improvements in methods for generating climate change scenarios are under development. One such method is the nesting of meso-scale meteorological models within general circulation models (GCMs) to improve regional climate change prediction (Giorgi and Mearns 1991). Another method is the use of stochastic weather generation models to generate synthetic daily time series with changes in variance, as well as means (Wilks 1991; Mearns et al. 1992). This is helpful because most impact studies so far have been limited to the investigation of the effects of mean changes in climate variables.

Some studies have begun to investigate the effect of potential changes in climate variance on the variability of crop yields, a key factor of agricultural stability. The question of agricultural sensitivity to climatic variability has been researched by superimposing past variations on altered average conditions to assess impacts for crop yields, farm returns and risks, and regional production in Ontario, Canada (Brklacich and Smit 1992), and the American midwest (Easterling et al. 1991). The effects of a range of temperature and precipitation variance changes, as well as future changes in variance predicted by one GCM, on simulated wheat yields in Kansas have been analysed by Mearns et al. (1992). Further investigation of climate and crop yield variabilities should be encouraged.

Improved prediction of potential future hydrological regimes (including estimates of changes in soil moisture and groundwater availability) continues to be a critical need for agricultural impact studies. Recent work on climate change scenarios suggests that the frequency of heavy rainfall events at almost all latitudes may increase with global warming, while the numbers of raindays in mid latitudes may decrease (Pittock et al. 1991; Whetton

and Pittock 1991). These changes may bring a nearly global increase in flood and high runoff events, leading to soil degradation and flood control problems, as well as reductions in the return period of droughts. Observations of hydrological variables, such as the recently published soil moisture dataset by Vinnikov and Yesserkepova (1991), should be useful in testing understanding of current and projected hydrological relationships. Still critically needed is the development of improved regional scenarios for monsoonal areas (Yoshino 1991).

Another key point which is emerging is that the emphasis of previous climate change studies on the arbitrary doubling of atmospheric CO<sub>2</sub> levels (or their equivalent) may be limiting estimation of impacts (Cline 1992). Atmospheric CO<sub>2</sub> concentration is projected to increase beyond doubling to 1600 ppm by the year 2250 (Sundquist 1990) and GCM simulations have shown large warming effects of CO<sub>2</sub> at such levels (Manabe and Bryan 1985). Greater warming beyond the equivalent doubled CO<sub>2</sub> level has implications for projections of agricultural impacts, because higher temperatures may lead to earlier maturity and lower yields of determinate crops in temperate regions, higher levels of potential evapotranspiration and water stress, and possible high temperature damage to yield quality (Wang and Hennessey 1991). While the climatic effects of CO<sub>2</sub> may negatively affect agricultural production at concentrations higher than doubled, the beneficial direct effects of CO<sub>2</sub> on crop growth may level off at higher CO<sub>2</sub> concentrations, as seen in experimental work on leaf photosynthetic rates (Akita and Moss 1973), leading to potentially greater negative impacts later.

### 2 Assumptions concerning technology and management

Since the publication of the first IPCC Impacts Assessment, there has been a growing emphasis on the need for 'moving' pictures of how agriculture may respond to transient climate changes over time. Research has begun to grapple with how such transient projections of agricultural technology should be estimated (Rosenberg and Crosson 1991). For example, conventional plant breeding and biotechnology are each expected to improve yields on the order of 1–2%/year (Pimentel et al. 1992) and such estimates should be factored into projections of future impacts of climate change. Other probable future changes in agriculture include higher fossil fuel prices and greater use of crops for fuel and paper fibre.

The vulnerability of crops to climate change may be either increased (by design) or diminished (inadvertently) by future technological changes. If technological advances

narrow the optimal range of input conditions for agricultural production (eg need for high levels of fertiliser), and if climate change results in increased variability such as increases in frequency of droughts as well, production risks may also be expected to increase.

### 3 Potential impacts on agriculture and land use

#### 3.1 Critical types of climatic change

In the area of direct climatic effects on crop growth, recent work shows that continued concern for future agricultural production appears warranted, a confirmation of the IPCC conclusions. Drought frequency may indeed increase in low and mid latitudes owing to increases in the demand of the atmosphere for water (potential evapotranspiration) over the supply (precipitation) (Rind et al. 1990) and to higher frequency of occurrence of dry spells (Pittock et al. 1991), although direction of change in climate variability of temperature and precipitation overall is still uncertain (Mearns et al. 1992).

Other critical types of newly identified climate effects are slight amounts of warming in the early stages of the projected climate change or increases in variability. These types of climate change may increase frost damage to crops (demonstrated by simulating wheat growth in Kansas), as slight warming or augmented variability actually lessens winter hardiness while not eliminating hard frosts altogether in some regions (Mearns et al. 1992).

#### 3.2 Regions of risk

Conferences since the advent of the IPCC have echoed the concept of regions at risk, based on preliminary projections of adverse climate change and present-day resource ability to support existing populations. More detailed descriptions of vulnerable regions and methodologies for integrated regional assessment of the potential effects of climate change have been brought forward, with emphasis on sensitive regions where farmers lack financial resources, fertile land, irrigation, drought-tolerant seeds, alternative employment options, or reasonable prices for inputs and products (Houston Advanced Research Center 1991). Jodha (1989) has shown that traditional farming systems encompass a wide range of adjustments to loss and advocates the preparation of an inventory of current farming practices available for transfer to regions with changing climates. However, Jodha also cautions that unequal social structures and international positions, as well as unequal land tenure, high numbers of landless rural dwellers, low incomes and

high national debts may increase vulnerability to climate change.

### 4 Direct effects of elevated CO<sub>2</sub> and other greenhouse gases

#### 4.1 Combined effects of climatic and direct effects of CO<sub>2</sub>

A fundamental question that remains despite continued research since the publication of the initial IPCC assessment is the overall relative importance of direct and indirect effects of CO<sub>2</sub> on future crop production. On an individual cultivar and crop basis these effects have been shown to vary considerably, depending on plant physiology and the coincident levels of CO<sub>2</sub>, temperature and water availability. Some scientists weight the beneficial effects of CO<sub>2</sub> as the dominant factor, while others are sceptical that the large benefits seen in experimental settings will be seen in farmers' fields under changing climate conditions. Free air release of CO<sub>2</sub> experiments on cotton are continuing in Phoenix, Arizona (Hendrey et al. 1992), and other free air release experiments are under way elsewhere (Miglietta 1991).

While the separate effects of atmospheric CO<sub>2</sub> concentration and temperature on specific plant processes have been studied extensively, the interactive effects of temperature and atmospheric CO<sub>2</sub> concentration over the entire growing season continue to be less well understood. Combined studies of direct and indirect effects of CO<sub>2</sub> on crops have intensified to provide clarification. A recently published review of these experiments showed that as temperature increased (levels not given), relative increases in plant growth and photosynthesis were greater under CO<sub>2</sub> enrichment (Allen et al. 1990). The extent of the temperature-CO<sub>2</sub> interaction differed considerably among species: C4 species were less responsive (as they have been shown to be to CO<sub>2</sub> increases alone) than C3 crops, and sorghum showed no response. The relative decrease in stomatal conductance to water vapour due to CO<sub>2</sub> was greater (as much as 25%) as temperatures rose.

There is a further need for studies of temperature and CO<sub>2</sub> interactions on crops and cultivars from diverse agricultural systems. These studies should be designed to test a wide range of levels of both factors and to quantify a full complement of crop physiological and phenological responses. Preliminary work suggests that potential crop responses to combined higher CO<sub>2</sub> and higher temperature may counter, at least in part, negative effects of climate change through gains in water use efficiency. From a regional perspective, however, water consumption per unit of land area may not change significantly due to plants

with larger biomass (Eamus 1991). Furthermore, given the trajectories for projected increases in greenhouse gases (GHGs) other than CO<sub>2</sub>, greater warming may occur with lower amounts of CO<sub>2</sub> and thus lower levels of CO<sub>2</sub> fertilisation (Cline 1992).

Because experimental settings are limited and costly, crop growth models are required tools for simulating the combined responses of crops to elevated CO<sub>2</sub> and climate change, especially at scales beyond one or several plants. Some of the efforts under way are described in Hesketh and Alm (1992) and Reynolds et al. (1992). Simulation models for wheat growth have demonstrated that higher temperatures cause earlier maturation, which can cancel out any gain in yield from higher CO<sub>2</sub>, and that only cultivars adapted to high temperatures may do well in a warmer and CO<sub>2</sub>-enriched environment (Wang and Hennessy 1991). These authors also cite experimental work showing that wheat quality can be significantly reduced by spells of high temperature above 35°C.

#### 4.2 Competition

A review of the implications of increasing CO<sub>2</sub> and climate change on competition in agricultural ecosystems has confirmed the original IPCC conclusion that differential growth responses to both CO<sub>2</sub> concentration and climate change will affect future competitive ability and fitness of plants (Patterson and Flint 1990). The relative importance of various weed species in agro-ecosystems may change, but selection of adapted crop varieties and management methods may minimise negative impacts. Weedy species with broad ecological amplitudes are likely to prosper at the expense of endemic species or those already in marginal habitats. In the tropics, important C4 crops such as maize and sugarcane, which are adapted to hot, dry conditions, may experience yield reductions because of the improved performance of C3 weeds (Bazzaz and Fajer 1992).

#### 4.3 Pest interactions

While experiments have tested some isolated aspects of pest infestations at elevated CO<sub>2</sub> concentrations, it is still hard to project future pest-CO<sub>2</sub> interactions. Some experiments have shown that some insect populations may decline owing to lower nutritional quality of leaves; this could lead to reconfiguration of many ecological interactions. Other experimental work has shown that insects consume more leaves in order to compensate for lower nutritional quality; this could work to negate benefits in

crop yields caused by higher CO<sub>2</sub> levels (Bazzaz and Fajer 1992).

### 5 Multiple stresses

It is important to emphasise that the future is projected to bring simultaneous multiple stresses, such as elevated UV-B radiation and augmented tropospheric ozone, in combination with high CO<sub>2</sub>, and that these may negate the beneficial physiological effects in some crops. Higher levels of CO<sub>2</sub> may partially offset damage from tropospheric ozone, sulfur dioxide and other pollutants, through stomatal closure (Allen 1990). Experiments reported by Teramura et al. (1990) show that no increase in wheat or rice grain yield occurred under conditions of combined elevated UV-B and CO<sub>2</sub>. Soybeans, on the other hand, produced more yield under the same conditions. A review of experimental literature has shown that susceptibility to plant pathogens may increase with higher UV-B radiation (Pimentel et al. 1992).

### 6 Effects of climate change on soil properties

New work has improved knowledge of the soil as a source of GHGs and of the potential impacts of climate change on soils (Buol et al. 1990; Bouwman 1990; Scharpenseel et al. 1990; US National Science Foundation 1992). Global climate change will affect soils primarily through changes in soil moisture, soil temperature and soil organic matter. Higher air temperatures will cause greater potential evapotranspiration and higher soil temperatures, which should increase solution chemical reaction rates and diffusion-controlled reactions. Solubilities of soil and gaseous components may either increase or decrease, but the consequences of these changes may take many years to become significant.

A study of potential land degradation in New South Wales, Australia, predicted significant increases in soil erosion, sedimentation and salinity if rainfall intensities increase (Aveyard 1988), while a study of soil erosion potential in the US using the Universal Soil Loss Equation found that national average sheet and rill erosion changes are projected to range from about -5% to 16% (Phillips et al. 1991).

Higher temperatures will accelerate the decay of soil organic matter, resulting in release of CO<sub>2</sub> to the atmosphere and decrease in carbon/nitrogen ratios, although these two effects should be offset somewhat by the greater root biomass and crop residues resulting from plant responses to higher CO<sub>2</sub>. The tendency of increased temperature to increase decomposition may also be offset

by the negative impact of increased carbon/ nitrogen ratios on decomposition, and the negative impact of drought on decomposition, if droughts become more frequent in a warmer climate. Higher temperatures could also increase mineralisation rates, improving availability of phosphorous and potassium and speeding colloid formation.

### 7 Effects of climate change on the distribution of agricultural pests and diseases

Recent reviews echo the earlier IPCC conclusion that ecological conditions for insect growth and abundance are expected to improve overall through lengthening of breeding seasons and extension of ranges (Porter et al. 1991; Pimentel et al. 1992), but also suggest that drier conditions may decrease pest damage in some regions. Porter et al. (1991) investigated the impact of one GCM climate change scenario on the European corn borer (*Ostrinia nubilalis*) in Europe, finding northward shifts in potential distribution of up to 1220 km, and an additional generation in nearly all regions where the insect is currently known to occur.

Pimentel et al. (1992) considered the effects of a 2°C temperature rise in the US and Africa and found that, if North America becomes warmer and drier, crop losses due to plant diseases are expected to decline as much as 30% below current levels. If Africa becomes warmer and wetter, crop losses to diseases will increase up to 133% above current levels for some crops. High percentages of crop losses to pests are expected to be sustained in Africa because effective pest control technologies are not extensively in use, nor are they expected to improve appreciably in the future. US crop losses to weeds are estimated to rise between 5% and 50% (depending on the crop), because of intensified competition from weeds, which are often better adapted to arid conditions than are crops. Herbicidal controls tend to be less effective under hot/dry conditions than they are under the more cool/wet current conditions (Pimentel et al. 1990).

## 8 Research on regional impacts

Note: the following section summarises recent research on both 'Potential effects on crop yields and livestock productivity' and on 'Effects on regional and national production,' determining if the research upholds previous IPCC findings or indicates new conclusions.

Another focus of substantial amounts of research activity since the first IPCC synthesis has been regional assessment. Some of the regional assessments have been conducted or are under way in the EC (Carter et al. 1991a,

1991b; Parry et al. 1992a), Rhine basin (Wolf and van Diepen 1991), US (Adams et al. 1990), US midwest (Rosenberg and Crosson 1991; Easterling et al. 1991), agricultural regions in Canada (Cohen 1991; Singh and Stewart 1991), East Asia (Yoshino 1991), Southeast Asia (Parry et al. 1992b), Caribbean region (Granger 1991), and Mexico (Liverman 1992; Liverman and O'Brien 1991). Fewer national assessments have been published, some exceptions being Hungary (Farago et al. 1990 and 1991), Ireland (McWilliams 1991), UK (UK Department of the Environment 1991), and New Zealand (Salinger et al. 1990; Martin et al. 1990).

As these regional studies come forward, they highlight the IPCC conclusion that impacts will vary greatly according to types of climate change and types of agriculture. Both beneficial and detrimental effects of climatic change are projected, although these will not be evenly distributed over the world. In particular, it appears more certain now that cool and temperate climatic zones may benefit, but in the tropics a further increase in temperature will be undesirable. At mid and high latitudes, increased temperatures can benefit crops presently limited by cold temperatures and short growing seasons. In the tropics, crops may be subjected to growing season temperatures higher than optima, and continue to suffer from nutrient shortages, which impair the potential to utilise the beneficial direct effects of increased CO<sub>2</sub> (Goudriaan and Unsworth 1990).

Newly published agricultural impact studies continue to emphasise the uncertainties inherent in such research as long as regional climate change scenarios remain unreliable. Other key uncertainties are projections of future technology and adaptation strategies. Methodological improvements are slowly accruing in dealing with such factors as direct CO<sub>2</sub> effects, pests and pathogens, increasing fuel costs and resource substitution, but many studies neglect one or more of these possibly key factors. Given these considerable caveats, researchers concur that regional impact studies should continue to be regarded as sensitivity studies only.

### 8.1 North America

#### 8.1.1 United States

Further results from the US EPA national study published since the IPCC Impacts Assessment imply a range of possible outcomes for US agriculture, depending on the severity of climate change and the compensating effects of CO<sub>2</sub> on crop yields (Adams et al. 1990). Simulations combining results from climate, crop and economic models indicate that the role of the US in agricultural export markets may change, regional patterns of agriculture are

likely to shift, and demand for irrigation water is likely to increase.

An integrated research project on the US midwest region (Missouri, Iowa, Nebraska and Kansas) used the 1930s climate (1.1°C increase in temperature) as a warmer and drier analog. Methodology included a crop simulation model and its use for evaluation of both available and induced adaptations; inclusion of technological change; analysis of climate variability effects on crop yield variability; and integration of impacts on multiple sectors including agriculture, forestry, water resources, and energy. The research found that impacts on agriculture overall would be small given adaptation (Rosenberg and Crosson 1991; Easterling et al. 1991). Relating these results to the IPCC best estimate of 2.5°C warming implies agricultural losses of about 10% for equilibrium warming of doubling of CO<sub>2</sub> equivalent (Cline 1992). However, at the margins of the region losses could be considerable with a shift in irrigation from west to east. Effective adjustments to the 1930s climate change scenario in the US midwest were earlier planting combined with longer season varieties of annuals and shorter season varieties in perennials, and the use of furrow dyking in warm season crops. Wheat benefited from reduction of cold stress and earlier break in dormancy.

Other recent research that used a simple relationship between yield and CO<sub>2</sub> and temperature reports similar yield declines for the US Great Plains (up to 42–45°N) (Okamoto et al. 1991). In summer, warming caused by increases in atmospheric CO<sub>2</sub> appears to be undesirable for spring wheat, soybean and corn even if positive effects of CO<sub>2</sub> are taken into account. Several CO<sub>2</sub> emissions rates were tested.

These studies support the IPCC conclusion that US grain production would decline with global warming. Another simulation with a mechanistic crop growth model with a soil water component found that grain yields at one site in Illinois increased, or decreased only slightly with temperature increases, except when the climate change was assumed to result in severely decreased rainfall (Muchow and Sinclair 1991).

For the southern US, research using a climate model, a crop growth model, and a field level pesticide transport model studied the impacts of climate change on various aspects of maize production (Cooter 1990). The results suggest that substantial changes in agricultural production and management practices may be needed to respond to the climate changes expected to occur in this region. These changes include the need for heat tolerance as the controlling factor in the introduction of new varieties, decrease in use of existing pesticides because of excessive loss on intensively cropped, rapidly leaching soils and an increase in the potential risk of aquifer contamination by long-lived

agricultural chemicals. Irrigation did not appear to be a viable solution to heat-stress-related maize yield losses in Texas and Oklahoma.

### 8.1.2 Canada

Research on potential agricultural climate change impacts in Quebec indicates that for one GCM (Goddard Institute for Space Studies (GISS)) climate change scenario, yields of corn, soybeans, potatoes, phaseolus beans and sorghum would increase and yields of cereal and oilseed crops, ie wheat, barley, oats, sunflowers and rapeseed would decrease (Singh and Stewart 1991). Apple and grape production might be enhanced and the northern part of the province would benefit most. However, even if climatic conditions in Quebec were to improve, limitations of soil fertility would still effectively constrain the significant expansion of the agricultural land base.

### 8.2 Central and South America

Several conferences have echoed the IPCC projections of possible negative impacts of global warming in Central and South America (Fundacion Universo Veinteuno 1990; Universidad de São Paulo 1990). Liverman (1991) and Liverman and O'Brien (1991) have used GCM output to project declines in moisture availability and maize yields at several sites in Mexico, following on from earlier studies cited in the initial IPCC Impacts Assessment. In contrast, a study of the implications for climate change and direct CO<sub>2</sub> effects in the Caribbean region found that agriculture and food supply should benefit, although more intense hurricanes and higher storm surges could bring added damage to low-lying coastal areas (Granger 1991).

## 9 Europe

### 9.1 European Community

Ongoing work for the European region, with a focus on the EC countries, is using a combination of techniques including large-scale mapping of agricultural potential, crop-climate simulation modelling and laboratory experimentation, to evaluate the possible effects of climate change on agricultural and horticultural production. Early results for grain maize, sunflower and soybean, all of which are constrained by low temperatures in northern Europe, indicated that northward shifts in crop suitability of 200–335 km per 1°C warming could be expected, with

these estimates varying locally by a factor of two owing to terrain and regional climate (Carter et al. 1991b).

For different GCM estimates of an equilibrium climate response to equivalent CO<sub>2</sub> doubling, estimates of northward shifts in potential due to warming varied from 700 to 1900 km. Rates of northward shift depend critically on the rate of warming. Regional estimates by the GISS GCM of transient climate response to low, middle and high emissions scenarios in Europe give shifts varying from 10 km per decade to well over 100 km per decade up to the 2050s (Carter et al. 1991a,b).

Further mapping work is examining the thermal and moisture constraints on grain maize production at a European scale. Crop yields are being estimated at individual sites, including winter wheat (different EC countries and four different crop models), cauliflower (ten locations in northern Europe), and soybean (France). CO<sub>2</sub> enrichment and temperature experiments with lettuce and carrot are also under way (Parry et al. 1992a).

### 9.2 Commonwealth of Independent States

Since the first IPCC Impacts Assessment, additional work has been conducted in Russia based on outputs from several GCM-based 2xCO<sub>2</sub> climate experiments. These indicate that the agricultural production level in Russia is expected to drop by 5-15% without direct physiological effects of CO<sub>2</sub> on crop growth and water use (Sirotenko 1991). In contrast, predictions based on palaeoclimate analogs show a significant rise in productivity in Russia for a doubling of atmospheric CO<sub>2</sub> (Sirotenko et al. 1990), especially when direct CO<sub>2</sub> effects are taken into account (Menzhulin 1992). A crop modelling investigation of winter and spring wheat yields with GCM scenarios combined with direct CO<sub>2</sub> effects has shown that winter wheat may respond more favourably to climate change than spring wheat (Menzhulin et al., 1992).

A review published since the IPCC assessment summarises research on climate change agricultural impacts in Russia with similar conclusions to those cited by the original IPCC (MacCracken et al. 1990).

### 9.3 Hungary

The Hungarian Meteorological Service of the Hungarian Ministry for Environment and Regional Policy has published several studies on climate change and its potential socioeconomic impacts. These volumes consider specific potential effects on Hungarian agriculture (Emanuel and Starosolszky 1990; Farago et al. 1990; Farago et al. 1991).

### 9.4 Ireland

The agricultural production potential of Ireland may be enhanced with climate change (McWilliams 1991). Production options could increase, new crops could be cultivated, and the overall costs of agricultural production could likely be less than at present. While cereal crops may have little or no increase in yields, yields of other crops like sugar beet and potatoes could increase by up to 20%. Crop regions could extend northward and new crops, such as maize, sunflower, and flax, may become viable over much of the south. Vegetable crops and fruit crops could be grown over wider areas than is currently the case, because warming should bring a reduction in the frequency of late spring frosts.

### 9.5 United Kingdom

In the UK, higher temperatures would decrease cereal crop yields, and increase yields of such crops as potatoes, sugar beet and forest trees (UK Department of the Environment 1991). Viability of grassland, animal production and forestry in the uplands would improve, but might require considerable investment. New crops and tree species could be introduced into the UK. Maize and sunflower might be grown for their grain yield as well as for fodder. Horticultural crops may benefit from warmer winters and reduced glasshouse heating costs. However, soils are likely to be seriously affected by climate change which encompasses variations in moisture, because cultivation may become more difficult under drier conditions, and because soil shrinkage could lead to more cracking with consequences for moisture balance, efficiency of fertilisers, herbicides and pesticides, and groundwater pollution. Land use policy for agriculture and agro-forestry may need to be reviewed in light of climate change effects.

### 9.6 Rhine Basin

Wolf and van Diepen (1991) estimated the effects of one climate change scenario (+3°C with seasonally varying precipitation changes) and doubled levels of atmospheric CO<sub>2</sub> on crop production and agricultural land use in the Rhine basin. Using a crop growth model, they found that the climate change and CO<sub>2</sub> scenario tested had generally positive effects on simulated crop production in the Rhine basin. Average grain production of winter wheat increased by 35%, average production of permanent grassland by 53%, while silage maize production decreased. Changes in land use induced by climate change projected on the basis of a literature review included an increase in area of

permanent crops, especially for vineyards; decrease in area of permanent grassland; decrease in areas cultivated with root crops, oats, rye, rape and turnip rape; and increase in areas cultivated with grain maize, sunflower and soybean.

## 10 Africa

Downing (1991) has presented a methodology for research on the potential impact of climate change in Africa that focuses on vulnerability to hunger (or food security), combining sensitivity to climatic variations with the multiple dimensions of regional and household food security. Downing et al. (1992) assessed the relative vulnerability of food production and needs to arbitrary climate change scenarios in several African countries. In Senegal, a 4°C warming would reduce crop yields by 30% by the middle of next century, which could leave an additional one to two million people without domestically produced cereals. In Zimbabwe, under a 2°C warming, yields that are currently achieved in seven out of ten years would be reached in only two to four out of ten years. In Kenya, climate change could increase total potential national production, while exacerbating food shortages in semi-arid areas.

A analysis of current crop yields and potential crop yield changes due to changes in temperature, moisture, UV-B radiation, CO<sub>2</sub>, pests, improved technology and losses to pests in Africa concluded that, if rainfall increases 10%, crop yields will improve to a limited extent (Pimentel et al. 1992). Water shortages may well persist, however, as well as serious crop losses to pests. The potential impacts of the greenhouse effect on Africa are a subject of regional concern (Suliman 1990).

## 11 Asia

A review paper on the climatic impacts on agriculture in East Asia suggests that year-to-year fluctuation of rice yields may become bigger, even though average yield may be greater (Yoshino 1991). This is based on statistical analysis of historical rice yields in Japan, which suggests that the fluctuation of yields is affected not only by climatic variability, but by step-wise development of technological and socioeconomic development as well.

A climate change agricultural impacts study in South-east Asia has been completed which used a climate change scenario developed from the GISS GCM and crop modeling techniques (Parry et al. 1992b). In Indonesia, average rice, soybean, and maize yields are projected to decrease about 4%, 10% and 50% respectively. In Malaysia, simulated rice yields decreased from 12% to 22%, while

demand for irrigation increased 15%. The east coast of Peninsular Malaysia may become too wet for rubber cultivation. Additional adverse effects on agriculture were estimated to occur in both Indonesia and Malaysia, and Thailand as well, as a result of land losses due to sea-level rise.

## 12 Australia/Oceania

### 12.1 New Zealand

In New Zealand, higher temperatures may result in substantial shifts in agricultural potential, with temperate crops, especially cereals, being grown 200 km further south and 200 metres higher for each 1°C temperature increase. At the same time, the potential range of these crops could contract southward if winter chilling requirements are not fulfilled (Salinger et al. 1990). The main horticultural crops (apples and kiwifruit) face displacement south of the present day main production areas. This could have serious implications for kiwifruit production, given the assumed climate change scenarios. Viticulture may expand south into the South Island with a change to red winegrapes in northern areas. Citrus and subtropical production might undergo expansion particularly in northern New Zealand. Animal industries could show substantial changes reflecting the change in the quantity and quality of seasonal pasture production and changes in pests and diseases. Dairying may decline in the far north, but could increase in the far south with temperature increases, resulting in an overall increase in production. At the same time, sheep numbers might show an overall decline, except in southern New Zealand. Beef cattle numbers are projected to increase in many areas of New Zealand with climate change.

## 13 Global assessments

The US Department of Agriculture has conducted studies of the sensitivity of world agriculture to potential climate changes (Kane et al. 1991, 1992). Preliminary results of these studies were presented in the first IPCC Impacts Assessment; recent results continue to indicate that the overall effect of moderate climate change on world and domestic economies may be small as reduced production in some areas is balanced by gains in others. However, further accumulation of GHGs could intensify the climate effects.

A recent global study of climate change and crop yield changes has estimated changes in yields of world crops in both major production areas and vulnerable regions caused

by GCM climate change scenarios and the associated direct effects of increasing levels of CO<sub>2</sub> (Rosenzweig and Iglesias 1992). Yield changes were estimated by crop specialists in 18 individual countries using compatible crop growth models and common climate change scenarios. Adaptations to the possible climate changes were also tested at two levels of effort. Preliminary results appear to amplify the IPCC conclusion that agriculture in lower latitude regions may be more vulnerable to the projected changes, even with adaptation efforts, because simulated yield declines tend to be greater in these areas in contrast to less negative or even positive yield changes at mid and high latitudes. When the economic consequences of the yield changes were projected in a world food trade model, results showed that cereal prices and the number of people at risk of hunger could increase with climate change (Rosenzweig and Parry 1992).

#### 14 Adaptation

While some recent reviews and studies have emphasised the possibilities of adaptation to climate change especially in developed countries (US National Academy of Sciences 1991; Rosenberg and Crosson 1991), conference statements and studies in the last eighteen months also suggest that it is important to remember that adaptation may not be complete and that some adaptive measures may have detrimental impacts of their own (Second World Climate Conference 1990; Smit 1991, 1992; Bazzaz and Fajer 1992). For example, changes in planting schedules and readily available cultivars may be easily adopted to minimise impacts on agricultural incomes, but modifying the types of crops grown does not guarantee equal levels or nutritional quality of food production or equal profits for farmers.

Similarly, irrigation is beginning to be perceived as a limited option for regions with increasing aridity caused by climate change. The integrated US midwest study found that agriculture may be less able to compete for surface water and that declining groundwater supplies would hasten the abandonment of irrigation in the western portions of the region (Rosenberg and Crosson 1991). Excessive overdraft of groundwater, soil salinisation, waterlogging, and potential increased demand from competing sectors may limit the viability of irrigation as an adaptation to climate change. However, studies continue to show that the need for irrigation is likely to increase with global warming, as was concluded in the first IPCC assessment. In the US, irrigation has been predicted to increase for a variety of climate change scenarios with higher temperature (Peterson and Keller 1990).

Regarding nutrient applications, Buol et al. (1990) project differing regional fertiliser use, as did the first IPCC Impacts Assessment. In temperate countries where crops are already heavily fertilised, there will probably be no major changes in fertilisation practices, but alterations in timing and application method (eg careful adjustment of side-dress applications of nitrogen during vegetative crop growth) are expected with changes in temperature and precipitation regimes. Fertilisation rates may need to be raised to utilise the beneficial direct effects of increased CO<sub>2</sub> (Goudriaan and Unsworth 1991). In tropical countries, where currently recommended fertiliser application rates are not always applied, augmentation of fertiliser applications will be needed in any case.

Adaptation to more intense pest infestations by increasing application of chemical control may increase chemical loadings in agricultural regions and may not be efficacious in regions where effective pest control technologies are not extensively in use nor expected to improve appreciably in the future. Therefore, high percentages of crop losses to pests may be sustained in such regions. Research has continued on the process by which farmers adapt, taking into account that imperfect information on climate change will be translated into incomplete and imprecise reactions by farmers (Yohe 1992). In this work, a utility-based decision model is used to test how farmers in the US midwest may decide to switch crops, or at least their mix of crops in response to growing evidence that the climate appears to be changing. Yohe suggests that consistent integration of these imprecise decisions over larger systems could add a sense of transition to static portraits of potential futures.

Kaiser et al. (1992) have similarly studied the process of economic adjustment in the US midwest to synthetic climate scenarios consistent with GCM predictions. This work finds that farmers in southern Minnesota can make some adjustments to mildly changing climate that may significantly moderate initial negative effects. This was due primarily to excellent water-holding capacity of the soil in the region tested.

Adaptation in agricultural policy is emerging as a necessary focus. Inertia and current policy structures may actually inhibit agricultural adaptation to climate change and variability (Smit 1991, 1992). Another study suggests that current US commodity programs may well slow adaptation to climate change by providing financial incentives for farmers to remain with existing cropping systems, rather than to switch to more climatically appropriate ones (Lewandrowski and Brazee 1992).

### 15 Gaps in research and monitoring

Critical research and monitoring gaps that remain to be filled include:

- Further experimental studies of temperature and CO<sub>2</sub> interactions over the full growing period on crops and cultivars from diverse agricultural systems are needed. These studies should be designed to test a wide range of levels of both factors, at varying water-stress levels, and to quantify a full complement of crop physiological and phenological responses and their effects on both biomass productivity and grain production. Studies should also be conducted on the interactions of CO<sub>2</sub>, high temperature, and other stresses such as elevated UV-B radiation and tropospheric ozone.
- Initial studies of changed climatic variability should be amplified by many more research efforts. The ability to test changes in climate variance is a needed advance in impact studies on agriculture, particularly for investigation of the effect of changes in climatic variances on variability of crop yields, farm returns and risks, regional production and key factors of agricultural stability.
- The viability of a wide variety of adaptation options (both biophysical and socioeconomic) needs to be tested for differing agricultural environments and systems. Research should be expanded in identifying the range of adaptability that exists within current crop species, in tracking the expansion of crop production into new environments, and in determining the physiological mechanisms whereby limits to production in stressful environments have been reduced so that the climatic range of successful production has been expanded. Research initiatives should continue to emphasise the processes by which farmers and institutions (both public and private) adapt, taking into account that imperfect information on climate change will be translated into incomplete and imprecise reactions by farmers, agricultural organisations and government agencies. Both economic and environmental costs and benefits of proposed adaptations should be evaluated.
- A needed focus is a better understanding of the linkages between climate impacts and socioeconomic structures and the critical thresholds where significant change takes place. Regions suffering from food poverty today need to be evaluated for vulnerability to the potential for increased stress from climate change. Much can be done to study ways to enhance resilience of agricultural activities to climate variability. Development of improved analytical models either generic

or specific to different agricultural systems in different regions of the world should be encouraged.

- While the agricultural sector (especially in regard to productivity) is probably among the most monitored of human activities, much could be done to analyse current and historical data for climate and CO<sub>2</sub> sensitivity. These types of studies can investigate, for example, how crop production regions have shifted geographically in the past, if they shifting now, and whether shifts are climate-related.

### 16 Recommendations and conclusions

Since the publication of the first IPCC Impacts Assessment, study of agricultural impacts of climate change has continued in many areas. The findings of these studies reinforce the conclusion of the IPCC Assessment Report that, globally, climate change should not compromise our ability to produce sufficient food. These findings also indicate that previous work may have overestimated negative, and underestimated positive, impacts due to climate change. However, there is a need for improved regional climate models and the extension of GCM simulations beyond the equivalent CO<sub>2</sub> doubling point, as well as a need for projecting how our agricultural systems will be configured in the future.

The available studies suggest, however, that the impact of global warming on agriculture may be significant, especially if warming is at the upper end of the range projected by Working Group I. Impacts of climate change must be considered in the context of the necessity for continuing increases in regional agricultural production as the world's population grows from 5 billion to a projected 8.5 billion by 2025. The following points summarise the contributions that recent studies have made to the field of agricultural climate change impacts.

Present studies have focused attention on how transient projections of agricultural technology should be estimated. For example, conventional plant breeding and biotechnology are each expected to improve yields on the order of 1-2%/year, and such estimates should be factored into projections of future impacts of climate change. Evaluation of a wide variety of adaptation options is needed for differing agricultural environments and systems.

Many regional assessments have been conducted since the IPCC, or are under way in the EC, Russia, the US midwest and agricultural regions of Canada, Southeast Asia and Mexico. Additional national assessments have been published by the Hungarian Ministry for Environment and Regional Policy, the Ireland Department of the Environment, UK Department of the Environment, and the New Zealand Ministry for the Environment. Additional

integrated regional impact studies linking biological, physical and socioeconomic factors should be carried out wherever possible.

As these regional and national studies come forward, they highlight the IPCC conclusion that impacts will vary greatly according to types of climate change and types of agriculture. Beneficial and detrimental effects of climatic change will not be evenly distributed over the world. In particular, it appears more certain now that cool and temperate climatic zones may benefit, but in the tropics a further increase in temperature will be undesirable.

Research continues to address the relative importance of direct and indirect effects of CO<sub>2</sub> on future crop production. Some scientists weigh the beneficial effects as the dominant factor, while some are sceptical that the large benefits seen in experimental settings will be seen in farmers' fields under changing climate conditions. Combined studies of direct and indirect effects of CO<sub>2</sub> on crops have been intensified to provide clarification. A key point which is emerging is that the warming effects of CO<sub>2</sub> are projected to increase beyond doubling point, but direct physiological effects may level off. The future is also projected to bring simultaneous multiple stresses, such as elevated UV-B radiation and increased tropospheric ozone, in combination with high CO<sub>2</sub>, and these may negate some of the beneficial physiological effects in some crops.

Recent studies have reinforced the concern for increased incidence of both droughts and floods, and on water resources for agricultural in general. Changes in water resource availability (both in timing and quantity) pose the greatest risks to agriculture resulting from climate change. Thus, water resource management for food and fibre production (in relation to water needs for other sectors as well) is a crucial task.

Current reviews confirm the earlier conclusion of the IPCC that ecological conditions for insect growth and abundance are expected to improve overall.

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## II The managed forest and the forest sector

### Scope of the issue

For the purposes of this report, the managed forest includes all forests in which some harvest takes place, with particular emphasis on forests where there is some degree of management. The majority of these managed forests are still of natural origin. This classification excludes forest parks/reserves and wilderness areas.

Projected changes to forest ecosystems suggest changes in the geographic distribution of forest species and changes in the growth rates with the most significant changes likely in the temperate and boreal areas. New information available indicates that the productivity of the forest sector due to increased greenhouse gas concentrations and associated climate change may have been underestimated. However, the socioeconomic consequences of climate change for the forest sector could be significant in regions where economic and social welfare and development is highly dependent on the forest sector. The global ability of the forest sector to cope with climate-induced changes will depend on the near-term acquisition of knowledge through focused research and assessment and on prudent, timely and proactive forest management policies and strategies.

### Progress since the IPCC Impacts Assessment in 1990

#### 1 Socioeconomic importance of forests

Clearly, the dependence and the importance of forests to the national economies has not diminished. This was demonstrated in the previous assessment and the updates in Tables 1 and 2 serve to reinforce this statement. Likewise, management strategies are urgently needed for the adaptation, mitigation and protection of the forest sector.

Countries must continue to address the socioeconomic issues related to forests in their response to the impacts of global and climate change. For example, the São Paulo Conference in 1990 stated clearly that 'The warming of the earth is clear evidence that current patterns of economic activity are not sustainable.' The conference identified the vulnerability of a number of patterns of activity for the developing countries.

#### 2 Reforestation/afforestation and more managed forests

The need for reforestation/afforestation is a global issue that must involve all countries.

A recent report from the USA states that 'Except for CO<sub>2</sub> scrubbing, which is not a proven technology at this

time, reforestation is the only known post-combustion carbon abatement measure.' (Sanghi and Michael 1991). Various options for reforestation/afforestation explore the methods for the establishment of a variety of species and the potential increase in productivity. (Schroeder and Ladd 1991). The data are based on experiences in a developed country, but the approach has potential application in many countries, with different species, economic and forest sector infrastructures.

Data from the IPCC Impacts Assessment demonstrated the benefits associated with increasing levels of management and recent reports have continued to emphasize the need for precise costing of all options and the accounting of the multiple benefits of environmental, human, spiritual, ethical and economic values associated with forests.

There is an important and unpredictable, human component involved in the questions of impacts and subsequent responses concerning species and vegetation conservation. This is further compounded by the lack of change in the sociological and economic sciences to calculate the multiple benefits with any degree of certainty. For example, there has been no improvement on the regional scale, of the science, either in climate change or in the putative response since the publication of the IPCC Impacts Assessment (1990) although efforts in this field continue (Woodward and McKee 1991).

The human population must be seen as both a part of the solution (ability to respond) and part of the problem (population growth). Within this context, Forestry Canada, as part of Canada's 'Green Plan' (Anon 1991), has begun a community tree-planting program designed to encourage the planting of up to 325 million trees in urban and rural areas across Canada. By the year 2000, this will result in the absorption of some 5.2 million tonnes of CO<sub>2</sub>, thus helping to offset future carbon emissions by including the involvement of the public at large in this issue. In addition to Canada's Green Plan, the US has the Global Releaf Program of the American Forestry Association.

Recent public opinion polls indicate that, at least in developed countries, people are willing to pay for carbon sequestration via reforestation, although this will not address the whole problem. The potential willingness of society to exceed the costs associated with the desired level of sequestration would 'make possible even larger reforestation benefits.' (Sanghi and Michael 1991).

#### 3 Tropical deforestation

The rate of deforestation has increased by 90% during the 1980s, mainly by shifting cultivators, and is expected to continue to increase during the foreseeable future (Myer 1991). Most efforts to reduce deforestation have con-

centrated on commercial enterprises, such as loggers/ranchers, but they account for only 40% of all current deforestation.

Further work is needed to liberalise current economic theories to account for the human demands and behavioural shifts within society. For example, current studies indicate that the greatest impact on atmospheric carbon can be realised by halting deforestation compared to promoting reforestation. However, the former solution may not be realistic as 'the depletive pressure is likely to increase if only through growing human numbers and growing human demands.' (Houghton 1991). In addition, the IPCC Impacts Assessment (1990) summarised the substantial potential that exists to increase the growth performance of managed tropical stands with rates of carbon sequestration that are more than twice the rates of managed forests in temperate or boreal regions.

#### 4 Research and monitoring gaps

The IPCC Impacts Assessment (1990) listed many items worthy of support in relation to forest ecosystems in general. These were echoed in more detail in the Bangkok Forestry Conference report (June 1991): 'There was a need for better information on the extent of forests, including further effort to ensure that appropriate definitions were used for each forest type and objective.'. Other problems cited included the use of various nomenclature and the failure to include tree crops associated with agriculture and agroforestry in discussions of forest responses. Numerous urgent data needs are becoming increasingly apparent, including (but not limited to):

- the need for regional climate change impact studies (Graham et al. 1990, Overpeck et al. 1990, Smith et al. 1990).
- an improved understanding of the genetics/physiology of tree species.
- the identification of critical points within the carbon cycle such as soil carbon contributions and the response of plants to elevated CO<sub>2</sub> and climate change (Reynolds et al. 1992).
- a better understanding of the linkages between climate impacts and socioeconomic structures and the thresholds where change takes place. The Bangkok Technical Workshop to Explore Forestry Options (April 1991) stated explicitly that 'better information on the cost effectiveness of the social and economic basis for different options for global forest management, and on quantifying the multiple roles of forests, was an urgent research priority'. All results since then would seem to confirm the urgency of this statement. For example,

the Bangkok Forestry Conference (June 1991) recommended that the nations of the world should be 'living off the interest and not drawing down the principal of the earth's ecological capital (and this should be accomplished by) integrating economics and the environment into decision-making.'. This attitude, also stated at the São Paulo Conference (São Paulo 1990) and elsewhere (Woodward and McKee 1991; Schroeder and Ladd 1991) reflects a universal concern and the need for action.

Forest health monitoring programs, including forest climate observations above and within forests, need to be established to detect damage to forest trees and soils that may have been caused by anthropogenic causes by isolating damage not attributable to natural causes or management practices (Hall and Addison 1991, Miller 1991). Integrated monitoring systems based on observed or proxy climate data sources should also include changes in vegetation and soils attributable to other impacts on representative forest ecosystems. These health monitoring systems need to be flexible and adaptable to allow for their transfer to other countries within the global community. The ability to close this research and monitoring gap can be immediately and highly successful given the demonstrated state of science and technology for electronic climate and biological monitoring systems.

Forests are a most significant renewable resource of biomass, timber, and fibre. Due to their extent forests have a large effect on the global carbon cycle. They are at the same time sinks, sources and reservoirs of carbon. The role of forests to the global carbon cycle is universally recognised as a sink for carbon, especially in the temperate and boreal regions (Sedjo 1992, Kauppi et al. 1992), but forests also provide valuable benefits as resources in the short term and in the long term to biodiversity. However, there needs to be an increased effort to quantify the global carbon estimates and the socioeconomic benefits. This includes the development of analytical models that account for the exchanges of carbon within the ecosystem and the relative contribution of forests, under different assumptions such as species types, soil conditions and various land use patterns etc. Robust estimates of the costs of carbon sequestered through afforestation are needed. These science-based models would have wide applicability in other countries as a shared resource and should not be restricted by proprietary rights. The universality of this type of scientific transfer should be encouraged to facilitate changes in policy.

## 5 Recommendations/conclusions

- The data on resources reinforces the vulnerability of the forest in all countries. Climate change will impinge on the social and economic sustainability of these forests. Results since the 1990 IPCC Impact Assessment reinforce the political and economic urgency in this sector.
- More reforestation and afforestation programs are recommended. The major goal is to sequester carbon but other benefits must not be neglected. Policies must take a holistic view and consider the cumulative benefits of forests.
- Research needs must centre on regional impacts studies, process studies, and the establishment and definition of the socioeconomic linkages.
- Forest monitoring and development of analytical models are essential, and must be widely applicable, acceptable and consistent for all countries.
- Research leading up to the IPCC Impacts Assessment and subsequent work, has amply demonstrated the continuing need for intensive and accurate technical and financial cooperation to optimise the management of our global forest. This assumes that there are or will be programs in place that take advantage of local and regional opportunities, particularly, and wherever possible within institutional infrastructures.

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TABLE 1A. Summary of forest resources and forest management species (1987)

		Canada	USA	Austria	FRG
Productive Forest Land (million ha.)		244	210	3.0	7.3
Impact of Forestry GNP on Economy		506	415 000	95	244
(\$billion Cdn)	Import	1.59	15.44	1.1	506
	Export	16.87	8.73	2.48	4.98
<i>Managed Species:</i>					
<i>Canada:</i>	Picea spp., Pinus spp., Abies balsamea, Populus				
<i>USA:</i>	Picea spp., Pinus spp., Quercus, Carya, Acer, Fagus Betula, Populus, Abies, Larix, Pseudo Tsuga, Tsuga, Juglanis				
<i>Austria:</i>	Picea abies, Pinus sylvestris, Larix decidua, Abiel alba, Fagus sylvatica				
<i>Fed. Rep. of Germany:</i>	Picea abies, Pinus sylvestris, Abies alba, Pseudotsuga menziesii, Larix decidua, Fagus sylvatica, Quercus robur				

TABLE 1B. Summary of forest resources and forest management species (1987)

		Indonesia	China	India	Brazil
Productive Forest Land (million ha.)		45	122	45	350
Impact of Forestry GNP on Economy		85	260	246	250
(\$billion Cdn)	Import	0.22	3.38	0.22	0
	Export	2.00	0.68	0.2	1.22
<i>Managed species:</i>					
<i>Indonesia:</i>	Meranti romin, Tectonia grandis, Pinus merkusii, Pterocarpus indicus, Eucalyptus deglupta, Acacia decurrens				
<i>China:</i>	Dawn redwood, Cathaya, Golden Larch, Chinese swamp cypress, fokienia cedar, larches, Chinese fir, Korean pine				
<i>India:</i>	Dipterocarpus spp., Shorea robusta, Cedrus deodara, Pinus roxburghii, Abies densa, Picea smithiana				
<i>Brazil:</i>	Eucalyptus spp., Tectona grandis, Khaya spp., Swietenia macrophylla				

TABLE 1C. Summary of Forest Resources and Forest Management Species (1987)

		Kenya	Zambia	Finland	New Zealand	Chile
Productive Forest Land (million ha.)		1.1	4.1	18.2	2.8	4.7
Impact of Forestry GNP on Economy		1.7	2.1	96.9	23.2	16.4
(\$billion Cdn)	Import	0.02	0.09	0.4	0.16	0.16
	Export	0.004	0	7.15	0.55	0.48
<i>Managed species:</i>						
<i>Kenya:</i>	Ocotea spp., Myrica salicifolia,, Acaçia labai, Acacia abyssinica, Podocarpus gracilior, Juniperus procera					
<i>Zambia:</i>	Brachystegia spp., Jubernardia angolensis, Eucalyptus grandis, Pinus kesiya					
<i>Finland:</i>	Picea abies, Pinus sylvestris, Betula pendula					
<i>New Zealand:</i>	Pinus radiata, Podocarpus totara, Rimu cupressinum, Kamaki, Rata					
<i>Chile:</i>	Pinus radiata, Eucalyptus spp., Populus, Pinus					

TABLE 2A. Roundwood production, imports, exports and their value (1989\*)

	Indonesia	China	India	Brazil
Roundwood production (thousand m <sup>3</sup> )	175 730	274 590	269 451	255 455
Roundwood imports (thousand m <sup>3</sup> )	0	13 383	902	26
Value (Cdn\$000)**	0	1 435 171	104 260	6 574
Roundwood export(thousand m3)	1 131	21	76	46
Value (Cdn\$000)	38 910	21 749	1 032	4 525
	Kenya	Zambia	Finland	New Zealand
Roundwood production (thousand m <sup>3</sup> )	35 650	12 204	46 262	10 557
Roundwood imports (thousand m <sup>3</sup> )	0	0	6 784	5
Value (Cdn\$000)	0	0	307 774	3 383
Roundwood exports (thousand m <sup>3</sup> )	0	0	1 047	2 470
Value (Cdn\$000)	0	0	97 825	138 254

TABLE 2B. Roundwood production, imports, exports and their value (1989\*)

	Chile	Canada	USA	Austria	FRG
Roundwood production (thousand m <sup>3</sup> )	16 864	176 976	533 168	16 086	35 332
Roundwood imports (thousand m <sup>3</sup> )	0	4 268	3 471	4 832	3 909
value (Cdn\$000)	0	223 542	149 221	298 007	445 675
Roundwood exports (thousand m <sup>3</sup> )	4 679	5 093	28 232	1 722	5 489
value (Cdn\$000)	188 362	424 400	3 348 651	93 118	366 181

\* FAO Yearbook Forest Products 1989—Published in 1991

\*\* Exchange Rate 1 CDN\$ = 1.183432 US\$

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## V Natural terrestrial ecosystems

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# V Natural terrestrial ecosystems

## 1 Background

As identified in the IPCC Impacts Assessment (1990), natural terrestrial ecosystems could face significant environmental impacts as a result of the global increases in the atmospheric concentration of greenhouse gases and the associated climatic changes, as well as from the increasing UV-B radiation due to the atmospheric ozone depletion and the combined effect of biospheric oxidants and acidic depositions. The rate of these changes will be the major factor determining the type and degree of impacts. The type of disturbances resulting from climate change will be unique for each ecosystem and the community within, as each responds to the added pressure of a changing environment. Adding to the complexity of assessing these changes is that they could occur as a series of 'jumps' rather than in a uniform manner across an area like a 'moving wave' (Holten and Carey 1991).

The social and economic consequences of these impacts will be significant, especially for those regions of the globe where societies and related economies are dependent on natural terrestrial ecosystems for their social and economic welfare. Projected changes within natural terrestrial ecosystems suggest that changes in the availability of food, fuel, medicine, fibre, construction materials and income are possible.

## 2 Progress since the IPCC Impacts Assessment

One of the major issues arising from the impacts of climate change on terrestrial ecosystems is water availability. This will be of increasing concern as populations increase and the need for water for drinking and economic activity (eg irrigation) increase concomitantly. Recent studies suggest that while water use efficiency should be increased in a higher CO<sub>2</sub> atmosphere, the same amount of water could be used per unit area because of increased leaf area ratios due to greater biomass produced through CO<sub>2</sub> fertilisation. Furthermore, any benefits accruing from the more efficient use by plants of soil water would be lost if wasteful irrigation technologies, such as flood irrigation, persist.

There is evidence (Holten and Carey 1991) suggesting that:

- in boreal, alpine and arctic regions, mesic and hygric plant communities will in general be more sensitive to climate change than the xeric communities;
- in temperate and southern to middle boreal regions in Europe, major floristic and faunistic changes may take place in some of the thermophilous deciduous forests as a result of projected improved conditions for Dutch elm disease;

- rare and mainly middle and high alpine species may be threatened with extinction (directly or indirectly) by climate change; and
- migration barriers, both natural and anthropogenic, could prevent or delay dispersal of more temperate plant and animal species into Scandinavia.

The process of reduction of tropical forest on the African continent, first noted in the tropical rain forest areas of Zaire and Uganda about 9000 BP (Livingston 1975) with the arrival of humans, will continue unabated and even be reinforced by global warming, resulting in an accelerated reduction of tropical forest and the expansion of the arid zones of Africa (Magadza 1990). Projected climatic change is likely to lead to an encroachment of the Sahel syndrome into the savannas. This region supports approximately 200 million people and any adverse effects of climate warming could result in the worsening of already precarious production systems in the area.

The degradation of the savanna ecosystems has a further implication for animals and migratory birds. Many animal and bird species utilise savanna wetlands and shallow lakes, such as Lake Abiata in Ethiopia, Lake Turkana in northern Kenya and other rift valley lakes, the Kafue flats of Zambia and, in West Africa, the flood plains of the Niger and Senegal rivers, Lake Chad and several other water bodies. Decreased rainfall or soil moisture as projected by several climate models for the African savanna ecosystems suggests that large-bodied animals, such as the elephant, hippopotamus and the large bovines, are liable to be affected more adversely than smaller species. Many migratory bird species utilise seasonal wetlands, locally known as dambos, vleis or bugas in eastern and southern Africa. Songbirds (eg common whitethroat, sedge warbler) breeding in Europe and wintering in the Sahel have declined in years following droughts in the Sahel, apparently owing to reduced habitat and survival in the wintering grounds. Projected climate change of the order anticipated by several climate models will probably result in the reduction of many such habitats (Magadza 1990) and, therefore, could negatively impact on these animals and migratory birds.

Seasonal wetlands are also critical to waterfowl and other migratory birds in the Great Plains region of North America (Diamond 1990; Diamond and Brace 1991).

In sub-humid savannas, climate change projections suggest increased aridity. It is therefore likely that rivers in these regions that show marked seasonality in flow would have reduced flows during periods of drought. Furthermore, many shallow water bodies, such as Lake Chad, could experience complete aridity during extended drought periods, or experience very high salinity levels. Such episodes would result in eventual extinction of the

fish species in those water bodies. Since many river basins display some degree of endemism, such species decimation could lead to reduction in species diversity, where only those types, such as the Claridae, which can readily migrate between river basins, would have the potential to survive.

Projected climate change may be one of the most important factors affecting fisheries now and in the next few hundred years. The level of the impact could vary widely and may depend on attributes of the species as well as on their regional specificity. Freshwater fish populations are contained within the bonds of their watershed and in most cases cannot migrate, but must endure (Shuter and Post 1990), adapt, suffer population declines or become extinct (Coutant 1990) when their environment deteriorates.

The added stresses to the freshwater ecosystems accompanying projected climate changes can be expected, in the short term, to reduce species number and genetic diversity within freshwater populations (Everett, in press). Species that survive a changing environment will likely be the ones with adequate existing genetic variation to allow survival and selection of at least some individuals. Whether the projected rate of climate change is within the capability of freshwater species to adapt genetically will depend on the existing genetic variability and on the rapidity of change (Mathews and Simmerman 1990).

With projected climate change, profound impacts, both beneficial and destructive, can be expected for the distribution and productivity of valuable fisheries and the industries associated with them (Healey 1990; Hill and Magnuson 1990; Johnson and Evans 1990). Among the first fish populations responding to climate change will probably be those in streams (a high rate of heat transfer from the air) on the warm or cold margins of their species' native ranges (Holmes 1990). With warming, a longer growing season is expected which should lead to greater fish productivity where temperature is currently a limiting factor, such as in high latitude lakes and reservoirs (Schlesinger and McCombie 1983). Species whose current distribution is confined to cool waters may be eliminated from parts of their range, leading to reduced fisheries, in spite of higher growth rates of the species that can tolerate warmer water.

Photosynthesis in plants grown at elevated concentrations of carbon dioxide is often reported to be reduced after a few days or weeks exposure. This reduction is often attributed to acclimation of carbon metabolism. Some studies of photosynthesis response to elevated CO<sub>2</sub>, however, show either an increase or no reduction in photosynthesis capacity. For example, data collected over four growing seasons on two monospecific stands: one dominated by a C3 sedge and the other by a C4 grass (in

a mesohaline salt marsh on the Chesapeake Bay) exposed to twice normal CO<sub>2</sub> concentrations showed increased carbon accumulation of 88% and 40% respectively.

Callaghan and Carlsson (in press) showed that high productivity is not necessarily commensurate with successful reproduction and greater fitness. This is particularly true in short growing seasons (eg due to temperature limitations in the tundra or aridity in the tropics) when climate conditions within the growing season allow high productivity, but the shortness of the growing season restricts successful reproductive development. Climate change projections suggest that in tundra areas, the growing season may lengthen as a result of warming; however, in other areas, increased aridity may shorten the growing seasons. This suggests the importance of considering population dynamics of plants as well as productivity. Such approaches also consider age-related processes and show that long-lived plants (eg trees), and those reproducing sporadically (eg many high-latitude and high-altitude plants), are threatened more by climate change than short-lived plants (eg annuals) because of the limitations on adaptive responses within each generation.

The report 'Arctic Interactions: Recommendations for an Arctic Component in the International Geosphere-Biosphere Programme' (1988) stresses the point that estimates suggest that 200–400 GT (109 metric tons) of non-oxidised carbon is stored in circumpolar peatlands (mostly in the boreal zones of Canada, the USSR and Fennoscandia). If a major part of this carbon were released because of changes in surface temperature and moisture—a physical possibility under projected climate changes over a few decades or centuries—then northern regions could emit a substantial additional amount of carbon to the atmosphere (potential positive feedback).

In their draft map of ecoclimatic sensitivity regions, Holten and Carey (1991) have suggested that within Norway, mountain and subalpine environments are the most sensitive to climate change, through climate-induced changes in snow cover (depth and duration) and hydrology. The arctic and flat river valley regions appear to be as sensitive as the alpine and subalpine environments.

### 3 Uncertainties and knowledge gaps

Uncertainties and gaps in the knowledge base exist in terms of our understanding of the environmental impacts for natural terrestrial ecosystems and associated socioeconomic consequences of climate changes. These uncertainties and gaps exist as a result of deficiencies in our theoretical knowledge of:

- Fundamental ecological process: effects of a changing set of interactive environmental parameters on plant net primary productivity and water use, ecosystem carbon and nutrient budgets, vegetation structure, species composition, forage quality, plant-animal and vegetation-soil interactions; population dynamics of major species and vegetation types as well as of pests and noxious species; and migration rates and mechanisms for species dispersal and settlement including the impacts of barriers and corridors.
- Linkages between climate and atmospheric chemistry changes (ie elevated levels of atmospheric pollutants such as SO<sub>2</sub>, NO<sub>x</sub> etc and atmospheric fertilisers) on the one hand and population and ecosystem dynamics (including implications for competitiveness, reproduction and productivity) on the other, can provide an assessment of the sensitivity (including buffering capacity, plasticity and resilience) of key species, communities or ecosystems.
- Linkages between ecosystem dynamics and human social and economic development and welfare under a changing climate can provide an assessment of the vulnerability of social and economic systems to changes in natural terrestrial ecosystems.

The significance of the environmental impacts and socio-economic consequences as a result of climate change (IPCC Impacts Assessment 1990) and the need to develop viable and effective response strategies warrants the allocation of sufficient resources to tackle these deficiencies through climate impacts research, management, awareness raising, national and international cooperation etc.

Within many developing countries, most of the climate change impacts activities (and for the environment in general) are orchestrated by outside agencies with little input from local scientific/technical experts. The capability of developing countries of taking long-term views and to initiate programs on climate change impacts is hampered by lack of the necessary institutional framework. In addition, the monitoring networks within many developing countries are either too sparsely distributed or unserviceable to allow for a worthwhile assessment of the impacts of, and responses to, climate change at the regional level.

The most urgent need is for fundamental research on the sensitivity and likely response of key physical and biological constituents of critical ecosystems (including those locally defined) to climatic variability and change. This research should also include wildlife and freshwater fish populations for which currently there is very little information available.

There is also a need for more attention on the implications of climate change for heritage sites and reserves. It

has been estimated that 25–60% of the present heritage sites and reserves could be unfit for the current species/communities they protect under projected changes in climate. This suggests that areas of adaptation will be required and that management strategies (ie in relation to desiccation and pest/disease control), adjustment of policies on selection/siting of protected areas and the development of specific studies and protective measures, should be required for 'transferral' of threatened plants and animals to suitable habitats.

The correlative relationships between climate and plant and animal species need to be experimentally evaluated to establish causal relationships and the relative impacts of changes in climate compared to other controlling factors. This comparative analysis is essential as there are other factors that can and are contributing to ecosystem disappearance and degradation (eg urbanisation, atmospheric pollutants, land conversion, agricultural land management practices, water course alterations). This requires that fundamental ecological research be done in parallel with research on socioeconomic responses (eg development of impact models that bridge the gap between environmental impacts and social and economic consequences) as ecological response may well be determined as much by socioeconomic reactions to climate change as by climate change itself.

#### 4 Addressing the uncertainties and knowledge gaps

To reduce these uncertainties and gaps in our knowledge, integrated national, regional and global programs and networks of research and systematic observations are required. These should include the improvement and further development of the global network of research and integrated systematic observation sites (eg Terrestrial Ecosystem Monitoring and Assessment (TEMA) of UNEP, Global Change and Terrestrial Ecosystem or using previous IBP research sites) with the aim of examining the linkages and relationships essential to defining environmental impacts and identifying where and what action is necessary. Also essential is the need to increase the skills of human resources and level of supportive funding available for participation in global programs and networks, especially for developing countries.

Integrated, representative, long-term systematic observation programs including biophysical, hydrological and meteorological parameters on a regional, national and global basis, as well as coincident economic and social (including health) data are a necessary building block towards reducing the uncertainties. These observation programs should combine relatively coarse data based on remote sensing with ground-based sampling over transects

on carefully chosen terrain covering the latitudinal/altitudinal extent of selected ecotones and ecotypes.

Systematic observations of population dynamics and ecosystem responses should support and be supported by field experimentation and modelling. Specific attention should be paid to vulnerable and critical (including those locally defined) habitats, typical ecotonal areas (eg Holten and Carey 1991) and species along steep climate gradients including margins and isolated populations, and coastal and island ecosystems as well as concentrating in transects across ecotones (desert-steppe/forest, savanna-steppe/forest, alpine timberline, forest-steppe and forest-tundra). These data should be archived in such a manner that they could be readily accessible. Heritage sites and reserves are excellent benchmarks against which to monitor the impacts of climate change and, therefore, should be considered as a priority when establishing a network of benchmark sites. Monitoring of more sensitive ecosystems and species should be given priority since they would provide early indication of impact of climatic change.

Remote sensing (satellite and radar, and the use of GIS) can be extremely useful for some aspects of monitoring ecosystem status and dynamics (eg geographic boundaries of vegetation zones). Ground-based or field observation, however, is also essential as a means of ground-truthing the remotely sensed data and for monitoring the subtleties in ecosystem and species responses which cannot be measured remotely.

Considerable progress could be made in a relatively short time by assembling and analysing existing data on interactions among climate, ecosystem and species dynamics, and social and economic parameters with the objective of identifying likely sensitivities and responses. The initial focus should be on ecosystems and regions considered most likely to be affected in the short term.

## 5 Fundamental ecological processes

An essential step in climate impacts assessments is to establish a consistent baseline of resources at risk through assembling relevant inventories of species and ecosystems on a national, regional and global basis. This will require development and acceptance of consistent protocols for identifying and making inventories of the boundaries, extent and dynamics of plant and animal populations (including disease and pest infestations) supported by field and laboratory manuals. Existing protocols should be evaluated for their sensitivity to the identification of the impacts of climate change, including whether or not they provide observation across current ecosystem boundaries and include vulnerable species/communities.

A comprehensive observation program designed to improve understanding of fundamental ecological processes should include two elements:

- broad-scale, low intensity, randomly or regularly dispersed sampling units (transects, plots, or points) to detect regional scale changes in the distribution and abundance of biota and distribution and integrity of ecological zones; and
- site-specific integrated monitoring projects located in sensitive ecosystems. These intensively monitored sites would also contribute to the understanding of cause/effect relationships between climate change, biota and ecosystems that is necessary to interpret the changes detected through the element noted above.

Peat dynamics is a key element in the prediction of future climate change. Studies of thermal and hydric regimes of peatlands should have high priority for research and systematic observation. In order to quantify the emission and storage of carbon by northern peat-rich ecosystems, refinement is needed of their present extent and carbon content.

Long-term ecological research sites should be present in each major ecological zone. Where possible, use should be made of existing sites where long-term information is already available. Strengthening the international agreements on ecosystem monitoring such as the US, USSR, Canada ecological transect in the northern latitudes should be promoted as a key component of the required research and monitoring program. Other monitoring programs, including the Man and the Biosphere (MAB) Reserves and UNEP/TEMA's Global network, should be instituted through appropriate agreements to develop a global standardised dataset. These long-term ecological research and monitoring sites would provide opportunities for intensive process-oriented research in addition to monitoring of effects.

Research efforts should include model development and assessment (both correlative and dynamic) and supportive controlled environment experiments and field experiments. Field manipulation techniques, at different levels within the ecosystem (ie at species, population or plant community level) are an essential component in addressing the uncertainties in understanding ecosystem processes and functions.

More field programs should focus on natural terrestrial ecosystem process research (eg what are the key climatic, hydrologic, geomorphological, biological and chemical processes that occur within these ecosystems and their interactions in determining ecosystem responses). Research topics to be addressed at the intra-specific level include physiology, phenology, regeneration and reproduction,

dispersal and migration. At the inter-specific level, research should focus on changes in plant-animal interaction (eg pollination), predation and competition, decomposition, and pest and disease dynamics.

With regard to entire life communities and vegetation complexes, research questions to be considered include changes in surface covering, vegetation structure, species composition, biomass, diversity and succession patterns.

Experimental work on specific interactions or specific variables are also required to understand cause and effect because of the complex interactions between environmental variables in nature. The International Tundra Experiment (ITEX) being developed for arctic studies, which includes basic systematic observations and environmental manipulations is one example of the type of program required.

## 6 Identifying the linkages with climate change and greenhouse gas concentrations

A focus for systematic observations of natural terrestrial ecosystems should be the identification of a set of wildlife and vegetation indicator species which could be used for detecting climate-induced ecosystem changes and to assist in quantifying vegetation, wildlife and freshwater fish sensitivity to climate and possible responses to climate change. Rather than trying to predict what will happen when climate changes, focus should be placed on assessing the sensitivity of species for climate change (thresholds/limits) in order to select indicator species which may be used to detect effects of climate change 'in the field'. In selecting indicator species consideration should be given to species which are expected to expand their range of distribution (horizontally and/or vertically), species which are expected to retreat or become extinct, and species which have a wide distribution with many ecotypes which may increase or decrease in abundance within the present range of distribution (Ketner and de Groot, in press).

Once identified, the distribution of indicator species should be systematically mapped using a grid system that lends itself to various modelling approaches, including computer-based models.

Related research should focus on identifying the cause/effect relationships between climate, ecosystems processes (eg biophysical, biochemical, geochemical processes), functions (eg habitat, water quantity and quality), distribution and productivity and associated wildlife and freshwater resources. Such research programs should be interdisciplinary by nature and not only assess the impacts of direct changes in climate, but also the effects of associated changes in soils, water regimes, and landscape structure and functions.

## 7 Identifying social and economic consequences

To identify and assess the social and economic consequences of climate change there is a need for directed monitoring and research programs at the national, regional and global levels. These programs should be multi-disciplinary, involving not only physical and biological scientists, but also representatives from the social sciences, including economics. National and international research funding should be capable of recognising and supporting this type of research.

These research programs should explicitly address impacts and consequences in the context of changes in non-climatic factors (eg population changes, economic growth, land use changes, lifestyle changes). Also included is the need to develop more realistic projections of supply, demand and use of natural resources 50 to 100 years from now, and to develop methods for characterising non-economic values of natural terrestrial ecosystems, such as scenic vistas, recreation, wildlife habitat and biodiversity.

Of particular interest when undertaking this type of research is information on the combined effect of both direct and indirect impacts on species and ecosystems. Examining the impact of a particular variable on a static environment and society, although interesting, is limited in its applicability. It would be more realistic to examine the impacts and consequences with fixed societal and environmental changes or, better still, with a responsive society and environment. These types of studies would lead to the identification of thresholds within both the natural terrestrial ecosystems and associated social economic structures.

Essential to these programs is the need to combine biological monitoring that can identify the ecological consequences of climate change with coincident data and information on associated social and economic systems. As a first step, existing databases comprising coincident physical and biological data, as well as social and economic information, should be identified. Assembling these databases will provide a means of undertaking the required impacts research and assist in refining the definition of the required research and monitoring programs.

To facilitate implementation of research and monitoring programs directed at identifying and assessing social and economic consequences of climate change, national and regional teams of experts representing the physical, biological and social scientific and economics communities should be assembled to undertake impact studies in an integrated fashion. This can be accomplished through strengthening existing programs at the global and regional levels. At the global level, the World Climate Programme and in particular, its World Climate Impacts and Response Strategies Programme should be encouraged to play a more active role in stimulating and facilitating regional assess-

ments. The establishment of regional programs such as the Landscape-Ecological Impact of Climate Change (LICC) program for Europe should be encouraged.

## 8 Conclusions

Promotion of the high and irreplaceable values of natural terrestrial ecosystems is essential in gaining public support for sustaining them in a changing climate. Action is also necessary to increase public awareness and to encourage support in their defence, as well as for enhancing the transcending importance of climate change impact studies and the assessment of their consequences and of the response options.

Managers, decision makers and local people need to be aware that policies and practices should be flexible to accommodate the implications of climate change and the dynamics of this change.

In the near term, the identification of sensitive species, communities and ecosystems should be one of the most important tasks undertaken. This sensitivity should be defined not only from an environmental perspective, but should also consider social and economic implications. As far as possible, the scale at which sensitivities are defined should be consistent with that at which decision can be made.

On the basis of these identified sensitivities, appropriate response strategies should be developed and implemented for those species, communities and ecosystems which face the most deleterious impacts (eg semi-arid and arid regions and tundra regions). Humans must be prepared to intervene where vital ecosystems or species are in jeopardy. In developing and implementing response strategies, consideration should be given to a wide range of response options, the specific local environmental, social and economic circumstances and the degree of uncertainties and risks.

Consideration should also be given to reducing major human-caused stresses such as pollution and those resulting from the impacts of other human activities such as logging and the grazing of domestic animals at subsistence level. These stresses may originate outside the boundaries of the affected ecosystem but often, once they are reduced, the elasticity of that ecosystem increases, possibly decreasing the impacts of climate change.

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## **VI Hydrology and water resources**

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# VI Hydrology and water resources

## 1 Introduction

Since the IPCC Climate Change Impacts Assessment report (1990b), a substantial number of studies have been undertaken that deal with the hydrologic effects and water resources management impacts of global warming. Although the body of information is growing rapidly, especially the proliferation of case studies of hydrologic impacts, few new insights have been offered by these studies, especially for water resources management impacts. This is due largely to the reality that the analyses are based on General Circulation Model (GCM) outputs which simply do not provide the information required for such analyses, nor are the results compatible with one another for the five GCMs most frequently cited (US National Academy of Sciences 1992). Overall, the recent studies have confirmed the findings and conclusions of the 1990 Impacts Assessment, albeit with nuances and refinements that were not explicitly considered then.

Among the difficulties in trying to interpret and compare the findings was that a great majority of studies were conducted without regard to conventional impact assessment and evaluation principles, while also ignoring IPCC global warming scenarios. This diminished their direct value in trying to understand the hydrologic response sensitivity, not to mention the comparative value in examining cross-regional impacts of global change on the vulnerability of comparably managed water resources. The impacts of climate change on watershed response and the vulnerability of managed systems presents a greater degree of evaluation difficulty; the few studies that have attempted to deal with these issues should be viewed in the context of an evolving yet tenuous methodology.

Even though evidence for global warming and its long-range impacts is becoming more compelling with each new report, like it or not, there is still considerable disagreement about the foreseeable regional hydrologic effects of global warming, not to mention the more complex socio-economic and environmental impacts associated with water resources management. *The reality is that generic global warming scenarios do not lend themselves to simple cause-and-effect extrapolations. There are countless simultaneous positive and negative feedback mechanisms to consider just to account for hydrologic processes alone. Water resources management impacts add an additional level of complexity.*

The hydrological cycle has emerged as the central element in studies of climate change

yet

at present a full 'systems view' of climate and the hydrological cycle has yet to emerge . . . . Climate models have yet to be developed which account for the full hydrological cycle and its interactions with the atmosphere, oceans and land.

(Chahine 1992).

Water resources management, by its nature, is intended and has served to ameliorate the extremes in climate variability. It stands to reason, then, that managed watersheds, ie those under some form of water control and distribution, are apt to experience less dramatic water resources impacts than those without such water management systems even though the natural hydrologic response may be similar. However, specific regional changes in precipitation and runoff are as yet impossible to predict with any degree of confidence (US National Academy of Sciences 1992; Chahine 1992). For hydrologic studies, precipitation is the variable of greatest interest, but GCM simulations of precipitation for *present* climate conditions are notoriously poor (Wood et al. 1992). Much attention has been focused on decreases in mean annual runoff, but some areas may well experience increased runoff, at least during the traditional seasonal peak flood period. Most model results do seem to forecast increased spring runoff for all the major rivers, although a comparative analysis by Kuhl and Miller (1992) and Miller and Russell (1992) suggest the reason may be that at least when considering the GISS GCM, that model uniformly overestimates mean annual streamflow and peak spring runoff when compared to historical records.

Thus far, the numerous impact studies are largely suggestive in nature, serving to prompt planners and policy analysts to search for worthwhile ways by which to account explicitly for and deal with potential changes in average runoff and a greater variability in climate in the foreseeable future. Water resources impacts are considered to be among the most significant consequences of climate change, along with ecological impacts, affecting especially the all-important agricultural sector. Hence, a degree of educated guessing is warranted as a way of better preparing for the uncertainties that lie ahead, at least in terms of preparing robust national strategies for coping with uncertainty. Potential effects in the agricultural, forestry and urban sectors, although of justifiable concern to warrant separate inquiries, are actually derivative problems stemming from the fundamental effects of climate change on water availability (quantity, quality, distribution and timing); and we must not forget that while the long-term implications of global warming have focused on water deficits and droughts, there is reason to believe that climate variability could also increase considerably, so that

societies must contend with large uncertainties at both ends of the hydrologic spectrum — floods as well as droughts.

Since the first assessment of the IPCC (1990a,b,c), scientists participating in the Impacts Assessment Working Group II realised that producing an estimate for water resources availability and other conditions extant within a climate that may exist 50 or 100 years hence, could be misleading at best, and completely unrealistic at worst. The reason is that the first step of analysing the cumulative consequences of global warming requires that the physical changes of hydrologic effects associated with climate change be differentiated from 'normal' climate variability as derived from historic records. Second, future water resources management impacts (water use, availability, distribution, operation and maintenance etc) should be viewed only as an increment (or decrement) to the water supply and use trends that are likely to occur under the 'baseline' or 'without' climate change scenario. The indicators of water use that reflect the baseline condition, projected over a period of 50 to 100 years will, in all likelihood, be dominated by population growth, economic growth, and patterns of land use and settlement. These socioeconomic changes would severely stress existing water management systems even under a benign climate scenario.

Clearly, climate change could exacerbate an increasingly complex resource management problem. Yet, the expectation is that, despite all the large uncertainties that infuse this issue, water resources management opportunities for adapting to climate change are perhaps better understood and offer more realistic promise to mitigate whatever adverse consequences that may materialise than our collective ability to predict, understand and manage future socioeconomic changes. This theme had been emphasised first in the IPCC (1990c) Response Strategies report and in subsequent reports by the US National Research Council (NRC 1991), the US National Academy of Sciences (NAS 1992), American Association for the Advancement of Science (Waggoner (ed.) 1990), and a conference of practising US federal water resources agencies and water utility managers (Ballentine and Stakhiv (eds) 1992).

The task of predicting regional hydrologic and water management consequences of climate change is a formidable one. At present, we can offer only a semblance of consensus on insights about how certain managed and uncontrolled watersheds could respond under a variety of climate change scenarios. Using the GCMs currently available, it is not possible even to replicate accurately current average climate conditions, much less forecast regional climatic conditions over annual and decadal time scales (Lins et al. 1990; Kuhl and Miller 1992; Chahine 1992).

The inability to forecast precipitation, runoff and evapotranspiration accurately should not be used as an argument to negate the application of GCMs to river basin level assessments, nor to diminish the value of undertaking hydrologic sensitivity analyses of the various postulated climate change scenarios. Rather, the caveats are intended to be cautionary in tenor - as a way of recognising that much too little is 'known' with certainty and spurious conclusions are drawn too often from information that is, at best, suggestive in nature. Towards this end, *the focus of future IPCC efforts should be to develop a more uniform methodology for impact assessments as part of a continuing effort of targeting regional river basin and country studies in order to obtain a reasonably comparable basis for evaluation.*

Hence, this update and assessment of recently available information is presented in the spirit of simply compiling the latest information, without a rigorous comparative analysis and evaluation, *for it is simply too difficult to judge the relative merit of various inquiries inasmuch as a formal and consistent evaluative framework is yet to be formulated. There are no accepted standards for analysis.* However, a number of principles and preliminary guidelines for assessing impacts of climate change were developed by an expert group assembled by the IPCC (1992d), but they have yet to be applied.

## 2 Overview of new information

This supplement to the first IPCC Impacts Assessment report summarises recent materials (1990–1992) that were solicited and received from many countries (Australia, Belgium, Venezuela, Canada, Indonesia, Israel, New Zealand, Norway, Peru, Switzerland, Poland, Romania, Senegal, USSR, USA, Uruguay, Finland, France, Chile, Japan), international organisations (WMO, UNESCO, IIASA, Commission on Mekong). Proceedings of international and national symposia and meetings on this problem held during the period 1991–92 in Japan, Denmark, Australia, Iceland, Uruguay, USA and Indonesia are also included, as are selected papers from conferences held on the subject and supplemented by published literature.

The studies and analyses that were made available subsequent to the IPCC Impacts Assessment which assessed the hydrologic and water resources management consequences of climate change reflected the range of approaches that have been pursued in the past by scientists, hydrologists and water resources engineers. These include: water balance methods; use of GCMs to obtain estimates of changes in climatic and hydrologic characteristics; use of deterministic hydrologic models; statistical analysis of long-term records; use of palaeo-analogues; and a combi-

nation of the aforementioned approaches. It is recognised that since the publication of the first IPCC Impacts Assessment, many studies have been initiated that rely on a comparison of GCMs but, with few exceptions, the final results were not yet available for this report. Similarly, many recent publications delve into better understanding of historical climate changes as an implicit analog or baseline for extrapolating future changes (eg studies of the El Niño phenomenon or the Sahelian drought). These studies were not included as they did not explicitly deal with evidence of hydrologic changes induced by *anthropogenic* global warming. Most studies focused on understanding the sensitivity of hydrologic response to climatic perturbations. Far fewer studies attempted to take on the more complicated problem of directly analysing the relationship between hydrologic watershed sensitivity and the vulnerability of managed water systems.

Methodological approaches varied widely, so it would be inappropriate to infer that the studies portray distinguishable patterns of regional or geographic response, despite the fact that the recent suite of water-resources-related climate studies cover a much larger and diverse geographic area. *It is impossible to draw any specific insights or conclusions about regional, river basin or watershed-level impacts because of wide differences among the GCMs and different analytical approaches that were used in these studies.* In other words, the impacts will depend on the characteristics of the river basin, the GCM selected, and on the particular analytical method pursued. Given the large uncertainties associated with GCM outputs, it is premature to use them for predictive purposes. At best, they may have a heuristic value for setting the stage for the next phase of detailed hydrologic impact studies.

Nevertheless, there are several recent noteworthy studies that shed some new light on the difficulties of conducting hydrologic sensitivity studies and potential water management responses, and which serve as cautionary reminders of a few principles and insights that may serve future endeavours. For example, Kuhl and Miller (1992) compared the GISS GCM hindcasts with observed runoff of the 20 largest rivers in the world and found systematic overestimation of the mean annual runoff. Furthermore, for several of the rivers (Mississippi, Amur, Colorado, Indus, Murray) the model's spring maximum runoff was significantly larger than observed, and the minimum summer and autumn runoff was too low.

Nash and Gleick (1991) studied the hydrologic response of the Colorado River (US) and compared their results, using a well-calibrated water balance accounting model, with several previous statistical studies for the same river. The authors concluded that the previous studies *overestimated* the decreases in runoff for the various scenarios involving increasing temperatures and that:

conceptual models of arid and semiarid basins suggest that streamflow is less sensitive to climate change than previous statistical models have indicated. . .

Furthermore, they conceded that changes in runoff to be expected under the selected range of temperature changes (up to  $\pm 4^{\circ}\text{C}$ ) would:

not be statistically different from the historical record unless precipitation changed by more than 10%. This confirmed a pathbreaking study by Klemes (1985) that had long been neglected by many analysts.

A critical aspect of water resources management is an understanding of the statistical properties of climate and weather-driven events, such as floods and droughts. For it is the extremes of precipitation and runoff that influence design criteria and management strategies. Little research has been done linking climate change with frequency of flood or drought, although several earlier attempts were made to place the implications of climate change and variability within the context of water resources system yield reliability using methods based on stochastic hydrologic analysis (Lettenmaier and Burges 1978; Matalas and Fiering 1977; Nemeč and Schaake 1982; Klemes 1985; Fiering and Rogers 1989). A recent study by Wood et al. (1992) laid out a procedure for assessing the impact of climate change on the flood frequency distribution for a river basin and tested the methods for  $\text{CO}_2$  doubling scenarios produced by the GFDL GCM. First, the authors note that the GFDL GCM failed to reproduce the historical climate characteristics for all seasons, uniformly underestimating precipitation for the two watersheds in the State of Washington in north-western US. In fact, the differences between historical precipitation and the present GCM climate simulations *were larger than the differences predicted between the GCM  $1\times\text{CO}_2$  scenario (present) and the  $2\times\text{CO}_2$  scenario.* Hence, the authors caution that while the effect of GCM model biases on their approach may be diminished by making relative comparisons, one could not be entirely certain because the models are highly nonlinear. Notwithstanding the caveats, the authors concluded on the basis of their test that stochastic transfer models offer a quantitative means of linking large-scale circulation conditions, as inferred from GCMs to local surface meteorological conditions, and can provide information for evaluating climate change impacts on flood frequencies.

A study conducted for a large semi-arid agricultural area in the US, the Missouri-Iowa-Nebraska-Kansas (MINK) area, was important for several innovative approaches and implications for water management (DOE 1991). The study approach was to postulate a recurrence of the most severe drought of record (1931-40) under

conditions of a doubled CO<sub>2</sub> climate in the year 2030, both with and without adjustments (such as water conservation, pricing, technological innovation etc). Detailed sectoral water uses, demands and projections were developed. For the MINK area, irrigation withdrawals were projected to increase by 14% and consumptive uses by 23% without employing rational adjustments. Crop yields would decline from 10 to 25% in the absence of adjustments, and plant requirements for irrigation water would *increase* by about 20%. However, as a compensating factor, it is expected that the direct effects of increasing CO<sub>2</sub> concentration from 350 to 450 ppm would *reduce* irrigation requirements by 10% (Easterling et al. 1991). Wollock and Hornberger (1991) examined changes in assumptions about the effects of plant stomatal resistance changes due to the CO<sub>2</sub> enrichment effect on the sensitivity of catchment runoff. They found that lack of good information led to large variability in the projections of runoff response. Most importantly, perhaps, is that despite all the uncertainties, the adverse regional economic impacts of such a drastic drought condition was found to be small, in the order of several percentage points reduction in total regional production (DOE 1991, p27).

A somewhat different approach to analysing the hydrologic effects of climate change was undertaken by McCabe et al. (1990). The authors examined the response of the Thornthwaite moisture index to climate change scenarios generated by three GCMs (GISS, GFDL, OSU). Their reasoning was that the Thornthwaite moisture index is a useful and early measurable indicator of water supply (precipitation) relative to its demand (potential evapotranspiration). Results showed that all three GCMs (steady state CO<sub>2</sub> doubling) predicted drier conditions for most of the US, although the amount of decrease depends on the GCM climate scenario selected. *Results also suggested that changes in the moisture index are related mainly to changes in the mean annual potential evapotranspiration as a result in changes in the mean annual temperature, rather than to changes in the mean annual precipitation.*

The greatest decrease in the index is expected to occur in the northern US, especially in the Great Lakes region, but only small decreases in the moisture index will occur in the already dry areas of the south-west US. It is important to note at this point that the parameterisation of continental evaporation in many atmospheric general circulation models is demonstrably inconsistent with observed conditions. In the turbulent transfer relation for potential evaporation, GCMs use the modelled actual temperature to evaluate the saturated surface humidity, whereas the consistent temperature is the one reflecting cooling by the hypothetical potential evaporation. Milly (1992) demonstrated that in GCM experiments where soil moisture is limited the models produce rates of potential evaporation

that exceed, by a factor of two or more, the rates that would be yielded by use of the more realistic consistent temperature. This explains why most GCMs have produced excessively low values of summer soil moisture and raises further questions concerning the results of studies of soil-moisture changes induced by an increase in greenhouse gases.

Finally, in one of the few available studies of the vulnerability of managed *urban* water resources systems, Kirshen and Fennessey (1992) analysed the potential impacts of climate change on the water supply of the Boston metropolitan area, which represents a large, well-managed urban water supply system. The study included a hydrologic analysis of various climate change scenarios, comparing the outputs of several GCM models (GISS, GFDL, UKMO and OSU) and an associated analysis of water management impacts, including financial and economic consequences and potential responses. The authors showed that the GISS and GFDL models generally predicted decreased watershed yield whereas the OSU and UKMO GCM scenarios indicated increases in runoff and increases in system safe yield. *As a result of these contradictory outcomes, the Massachusetts Water Resources Authority (MWRA) is taking a 'wait and see' response similar to that of other urban US water utility managers (Schwarz and Dillard 1990) because they believe that the impacts of climate change are too uncertain and the costs of action are too high to warrant such actions.* However, the MWRA has engaged in an aggressive program of cost-effective demand management and water conservation actions that, in effect, represent the foundation of a sensible anticipatory adaptive strategy. Similar institutional responses are expected in most urban metropolitan regions, whether the cause is growth in water demand or in water shortages caused by droughts or global climate change (Rhodes, Miller and MacDonnell 1992; Frederick 1992; Rogers 1992; and Stakhiv 1992).

### 3 Case study summaries

Studies have been carried out for the river basins and regions located in various natural climatic zones (temperate, high and middle latitudes, arid and semi-arid and humid tropical) as well as by using palaeoclimatic scenarios for the continents of the Earth as a whole. Temperate zones are most comprehensively presented in the studies on European countries for the river basins where most of the annual runoff is formed as a result of snowmelt in spring.

In Finland, a CO<sub>2</sub> doubling scenario generated by the GISS GCM model was used to estimate changes in runoff for 12 watersheds of 600 km<sup>2</sup> to 33 500 km<sup>2</sup>. Temperature

increases of 2 to 6°C and monthly precipitation increases of 10 to 30 mm were produced by the GISS model. The results showed 20 to 50% increases in mean annual runoff for individual watersheds, and a more stable interannual monthly runoff pattern for most watersheds (Vehvilainen and Lohvansuu 1991). Maximum spring discharges were found to decrease considerably (up to 55%) and minimum monthly flows to rise dramatically (up to 100 to 300%).

Hydrologic sensitivity studies in Norway relied on a comparison of two assumed (non-GCM) scenarios for CO<sub>2</sub> doubling by the year 2030. According to the first scenario, winter temperature would rise by 3.0 to 3.2°C, summer by 1.5 to 2.0°C and annual precipitation by 5 to 15%. According to the second scenario, by 3.5 to 5.0°C and 15 to 20%, respectively. The changes in runoff for seven regions in Norway were calculated by using an existing simplified conceptual hydrological model for a 30-year historic period and the two climate scenarios (Saelthun et al. 1990). The results show that annual runoff increased somewhat (up to 10 to 15%) in the mountainous regions and in the regions with large annual precipitation. In low forested areas, it decreased slightly. Seasonal runoff changes significantly: spring floods decrease; winter runoff increases substantially, while summer runoff decreases. The frequency of floods increases in autumn and winter (Saelthun et al. 1990).

Kaczmarek and Krasuski (1991) obtained very similar results for one of Poland's largest rivers, Varty (area is 54 530 km<sup>2</sup>), using CO<sub>2</sub> doubling scenarios generated by the GFDL model coupled with a monthly water balance hydrological model. With global warming the annual runoff of this river changes, but slightly. However, winter runoff rises (21%) and summer runoff decreases (24%). Similar results have been obtained for small and medium-sized watersheds in Belgium and Switzerland. Studies were conducted by Bultot et al. (1991) and Gellens (1991a;1991b) who applied GCM scenarios with the conceptual hydrological model of the Royal Meteorological Institute of Belgium with a diurnal time interval. For example, comprehensive studies of an experimental basin in Switzerland reveal relatively insignificant changes in annual runoff with increasing winter runoff by 10% and decreasing the summer one by 11% (Bultot et al. 1991)

For the nations of the former USSR, a set of improved scenarios of future climate with a 1°C and 2°C global warming based on palaeoclimatic analogues was developed in 1991 by a group of climatologists guided by Professor M I Budyko. These scenarios were used to obtain approximate estimates of potential changes in annual and seasonal runoff of main river watersheds. Methodologically, these computations are based on water balance methods (for average annual runoff) and hydrological models of river watersheds with 10-day time intervals. They

show that there are no statistically discernable changes in annual river runoff in the basins of Volga, Dnieper, Don, Ural, Zapadnaya, Dvina and Neman with a 1°C warming. There is an expectation of increased annual runoff (by 5 to 10%) on the rivers of the Caucasus and West and East Siberia. Somewhat larger increases are expected in the mountain rivers in Central Asia. However, the estimates obtained for mountainous regions are very crude because of great uncertainty of palaeoclimatic scenarios.

With a 2°C global warming, annual runoff in the major river basins of the former USSR increases more significantly. In particular, in the Volga basin annual runoff increases by 5 to 7%; in the Dnieper, Don, Dniester basins as well as in the Baltic River basins by 20 to 25%; in Siberia and the Far East by 10 to 20%. This trend also occurs in the mountain rivers in the Caucasus and Central Asia.

As to changes in monthly and seasonal runoff, the most detailed reconstructions have been made for the three largest rivers of the European part of Russia: the Volga, Dnieper and Don. Proxy records indicate considerable potential change in seasonal runoff. Winter runoff increases dramatically and spring runoff decreases significantly (Shiklomanov and Lins 1991), ostensibly in response to a shift in the snowmelt season from spring to late winter as temperature rises.

For most of Canada, global warming would increase annual river runoff and its intra-annual distribution except for the Great Lakes basin, where according to all the GCM scenarios, an increase in air temperature and decrease in river runoff are most probable. This could result not only in a changed water balance and lake level, but also in serious economic and ecological consequences (Hartmann 1990; Croley 1991; Quinn 1992).

The impacts of climate change on groundwater has received little attention, although a recent evaluation of Australia's major aquifers represents an awakening to the importance that groundwater recharge and management has in the overall scheme for water resources management. Ghassemi et al. (1991) have noted that precipitation trends have changed markedly in this century over Australia and they expect trends and patterns to continue with global warming. Overall, they conclude that for a large area of Australia, especially the populated south-eastern quadrant, where groundwater is already overdrafted, groundwater recharge will increase. The shallow aquifers in the arid and semi-arid zones of Australia (eg the Amadeus basin) will also benefit from increased precipitation and recharge. However, global warming will likely be detrimental for a number of major regional aquifers in south-western Australia, in the Perth basin and Murray basin, because of decreased rainfall.

Considering the qualitative results of the various studies of global warming effects on annual and seasonal river runoff in the northern and temperate zone of the Northern Hemisphere, *it would appear that* in the regions where a considerable part of annual runoff is formed during the spring flood, the intra-year runoff distribution appears to be more sensitive to air temperature changes than to annual precipitation. In this connection, projections of variations of seasonal runoff in these regions could be more reliable than of the absolute magnitude of annual runoff because the GCM temperature forecasts are thought to be more reliable than precipitation. Yet, research by Karl and Riebsame (1989) contradict that impression by showing that hydrologic (runoff) variability is almost entirely controlled by precipitation variability.

Estimates of global warming effects on hydrology in arid and semi-arid regions have been made for the southern area of the European part of the former USSR, Australia, some regions of the US, South America and Africa including Sahel (Nash and Gleick 1991; Urbiztondo et al. 1991; Australian Bureau of Meteorology 1991; Sirculon 1990; Vannitsem and Demaree 1991). The most recent case studies provide mixed and often contradictory implications, most likely stemming from the diverse methods applied and the divergence among GCM scenarios. However, there are indications that the earlier conclusions about the sensitivity of watersheds in arid and semi-arid regions to even small changes in climatic characteristics may be overstated (Nash and Gleick 1991). Nevertheless, it is apparent that annual runoff appears to be more sensitive to changes in precipitation than in air temperature for arid areas.

Analysing the hydrological implications of global warming in arid regions, the problem of the Sahelian zone should be emphasised, as a severe drought of the past decades caused disastrous consequences in many countries. The comprehensive analysis of climate change impacts on water resources of Sahel is presented in a study by Sirculon (1990) who emphasises a strong sensitivity of river systems to changes in climatic characteristics and consequent vulnerability of the water management system. As for the future of water resources in Sahel, there is a large amount of uncertainty because of contradictory data on future climate obtained by GCM computations and from palaeoclimatic analogs. Palaeoclimatic analog information suggests that global warming should lead to a large increase in precipitation in this region with relatively small increases in temperature, resulting in a considerable increase in runoff. However, according to the outputs of three types of GCMs (IPCC 1990a) which show that the air temperature in the Sahelian region rises by 1 to 2°C, with a doubling of CO<sub>2</sub>, the models show winter precipitation decreases of 5 to 10%, whereas summer precipita-

tion increases up to 5%. With this scenario, it is unlikely that runoff will increase because evapotranspiration will result in a net reduction in runoff.

In wet tropical regions, the assessment of global warming effects on water resources has been done for two river basins of Venezuela (Andressen and Rincon 1991); for the basin of the Uruguay River in Uruguay (Tucci and Damiani 1991; the Lower Mekong River basin (Mekong Secretariat 1990); the Ellagawa catchment area in the central part of Sri Lanka (Nophadol and Hemantha 1992) and Indonesia (Rozari et al. 1990). In these studies, the scenarios used are those inherent in the selected GCM, with CO<sub>2</sub> doubling and hydrological implications estimated by using a variety of conceptual, deterministic simulation models of river basins.

In the Sri Lanka study, Nophadol and Hemantha (1992) chose to compare three GCMs (GISS, UKMO and GFDL) with respect to their ability to replicate historic temperature and precipitation conditions. They concluded that for Sri Lanka the GFDL was least compatible and chose to continue analysis with the GISS and UKMO models. The authors concluded that under a doubling of CO<sub>2</sub>, the mean monthly and daily precipitation would increase during the peak rainy season, although no significant change in mean annual precipitation would occur. The peak precipitation period would shift from April–July to September–November. However, low flows would increase, as would severity of droughts.

The study by Rozari et al. (1990) relied solely on the GISS GCM transitional CO<sub>2</sub> doubling scenario. The authors selected this model because it generated rainfall results that best reflected the situation in Indonesia, according to their judgment. The study analysed the overall impacts on hydrologic sensitivity for Indonesia and then focused on three catchment areas in Java. Based on a general water balance analysis for the three watersheds, the analysis showed that, in general, the periods of water deficits are shortened by at least a month, with significant increases on monthly runoff for all months in all three watersheds. An associated study (Rozari 1991) analyses in greater detail the agricultural impacts of increased precipitation and runoff, citing increased erosion rates, reduction of soil productivity with consequent reduction in crop yields of up to 9%. Although the three watersheds are regulated by large reservoirs for flood control, hydroelectric power irrigation, municipal and industrial water supply and inland water fisheries, no analyses on water management impacts were conducted.

Andressen and Rincon, in a personal communication (1991), provide preliminary results of a study of climate change on the hydrology of three drainage basins in western Venezuela, ranging from 1000 to 25 000 km<sup>2</sup>. A relatively simple (6-parameter) monthly hydrologic simula-

tion model was used in conjunction with a Thornthwaite water-balance model. Three different (non-GCM generated) climatic scenarios were developed:

- (1) a low sensitivity scenario with no precipitation change and a  $+2^{\circ}\text{C}$  increase;
- (2) a medium sensitivity scenario with a 20% precipitation increase and a  $+3^{\circ}\text{C}$  increase; and
- (3) a high sensitivity scenario with a 40% precipitation increase and  $+4^{\circ}\text{C}$  increase.

Based on these hypothesised scenarios, the authors conclude that the streamflow peaks will not shift; that average annual streamflow will increase for the low and medium scenarios, but decrease slightly for the high sensitivity scenario.

In perhaps the best existing suite of comparative water management studies available, the US Environmental Protection Agency (1990) initiated a comparison of five complex river basin management schemes of the La Plata/Uruguay, Mekong, Indus, Zambezi and Nile Rivers. Only preliminary analyses of the Mekong, Uruguay and Zambezi Rivers were available for this assessment. A similar effort, undertaken by the United National Environment Programme (Parry, Magalhaes and Ninh (eds) 1991) compared impacts for Brazil, Indonesia, Malaysia and Thailand, although the analysis for Brazil examined only the impacts of current climate variability and drought on agriculture. Overall, the analysis for Southeast Asia was conducted by comparing three GCMs (GISS, GFDL, and OSU).  $\text{CO}_2$ -doubling analyses for Indonesia were focused on agricultural impacts, showing higher levels of precipitation, which increased the area of potential agriculture, but also increased soil erosion and loss of productivity. In Malaysia, there did not appear to be a significant change in the seasonal pattern in rainfall. Rice yields were expected to decrease because of an increase in temperature and decrease in solar radiation due to increased cloudiness. Results of  $\text{CO}_2$ -doubling for Thailand (GISS model) shows a warming of 3 to  $6^{\circ}\text{C}$ , and a significant reduction in precipitation. Northern Thailand would be drier in most months, which would be a benefit to agriculture in that area. Overall, the methods used were not comparable, and the results presented in these studies were inconsistent and highly variable among the three countries, as they were conducted by different groups.

The Mekong River is among the largest rivers in the world, with almost three-quarters of the watershed lying within the tropical zone; its climate is controlled largely by seasonal monsoons. In a study conducted by the Mekong Secretariat (1990), equilibrium scenario outputs of three GCMs (GISS, GFDL, UKMO) were compared for water resources impacts analysis, along with two transient

scenarios (exponential and arithmetic growth of  $\text{CO}_2$ ). For all the hydrologic stations analysed, all the climate scenario forecasts showed longer dry periods and wet periods. Also, the patterns of monthly rainfall generally shifted one to two months *earlier* in the monsoon season, along with the time of occurrence of the driest and wettest months. Generally, rainfall increased significantly in the wet months, while the decrease in the dry months was smaller, although the duration of rainfall-deficient months increased. Reservoir operations would have to change to accommodate the greater variability in peak flows and low-flow periods. Hydro-electric power production will be affected, but irrigation releases would not be affected. The authors concluded that new reservoir operation rules would mitigate many of the potential adverse effects.

In the study of the Uruguay River (Tucci and Damiani 1991), which was part of the triad of studies conducted for the US Environmental Agency, the authors generally followed the same approach as for the Mekong River. They compared three GCMs (GISS, GFDL, UKMO) with both equilibrium and transient  $\text{CO}_2$ -doubling scenarios. They found that *all* the models underestimate total historic rainfall, but that the GISS model performed the best in terms of replicating modern historic conditions. A hydrologic model was used to estimate flows in the Uruguay River from the precipitation generated by the GCMs. The predicted flows indicated an 11.7% decrease with the GISS model; a 21.5% increase with the GFDL and a 6.4% decrease with the UKMO model. The GISS transient model also showed an 11.7% reduction in mean flows.

All the GCM models predicted lower dry-season flows for the Uruguay River, but the models differed widely on the inter-annual variation of flows and on the magnitude of peak flows. The study did focus on water management impacts, as the basin is developed and managed for hydro-electric power, flood control, irrigation and water supply. Much more hydro-electric power is planned for the basin, hence the impacts on hydro-electric production was considered very important. However, the different models generated contradictory results. For example, the UKMO and GISS models predicted a decrease in hydro-electric power output of 2.5 to 4.75%, whereas the GFDL model showed an increase of 17.3%. Three of the four model scenarios predict smaller and fewer floods, resulting in flood damage avoidance benefits. However, reduction in low flows and lengthening of low flow duration was forecast, showing decreases of 3 to 18%. This implies a greater frequency of failure and water rationing, especially for irrigation withdrawals.

Analysis of the impacts of climate change on water resources management of the Zambezi River was conducted by Urbiztondo et al. (1991) for the US Environmental Protection Agency (1990). Preliminary results of

a rainfall runoff simulation analysis and comparison of GCM scenarios generated by the GFDL, UKMO and GISS models showed that runoff based on GFDL and GISS steady-state CO<sub>2</sub> doubling was consistently lower than the base scenario, representing current climate. The UKMO scenario projects an increase in river flow. The GISS Transient A and Transient B scenarios show decadal variations in precipitation, with decades of increases and decreases. The Middle Zambezi River is regulated by the Kariba Reservoir, a large multipurpose storage dam. A highly simplified reservoir optimisation model was used to examine the impacts that GCM-generated inflows would have on hydro-electric power generation. Kariba Reservoir generates up to 70% of Zimbabwe's electricity, so that any pronounced reduction in runoff or changed seasonality of flows would have a major adverse economic impact on that country. However, the simulation and comparison of various GCM scenarios, both stationary and transient, showed that annual target energy demands, based on a plant load factor of 65% and an efficiency of 95%, would be met under virtually all scenarios. Nevertheless, the impacts during dry years would be severe, as is the situation under present climate conditions.

#### 4 Water resources management impacts

Global warming is expected to catalyse changes in water management in many regions of the world. The quality and quantity of groundwater; the structure and character of water consumption might alter; the conflicts and contradictions among individual water users and consumers would heighten; and design and operational changes would need to be re-examined. All these issues have been treated, to varying degrees, for several river basins with prescribed climate scenarios both in the Northern and Southern Hemispheres.

Climate uncertainty and water management was the topic of two recent conferences in the United States (NRC 1991; Ballentine and Stakhiv (eds) 1992). Rogers (1992) addressed the role that uncertainty of climate change information played in decision making related to water management issues. Rogers essentially concluded that even if the GCM models were scientifically well grounded and their prediction considered perfect, the information provided is largely peripheral to practical engineering decisions. The reason is that hydrology and availability of water is only one among several important factors in water management decisions, which include economic, political, sociological, technological and demographic consideration. There are three categories of decisions in water resources planning and management: planning and design that goes into *new* investments; those dealing with the operation and

maintenance of existing systems; and those that modify the operational capacity of existing systems. There are many uncertainties faced by water managers and planners, not the least of which is future population and demand. Hydrologic uncertainty, ironically, may be among the less important considerations.

Sheer (1991), Fiering (1992), and Stakhiv (1992) make similar points in that planning water resources systems involves making many interrelated design and operating decisions under uncertainty. These decisions are made continuously and focus on the extremes and variability of the present climate. Various levels of buffering capacity, redundancy and resilience are built into individual design criteria and components of a water management project and its operation within a larger system as an inherent hedge against an unforeseeable event. Hence, managed water systems, while not entirely fail-safe, are designed to be robust enough to guarantee a high degree of reliability for rare or extreme events within the historic record. These rare events may become more frequent as part of a potential shift in the climate mean and variability. But planners and designers are constantly adjusting their design criteria and, in effect, are anticipating subtle changes in the statistical properties of the evolving record of precipitation and streamflow. In addition, new and more sophisticated techniques are employed to optimise the capacity, operating rules and economic efficiency of the upgraded water management systems.

Furthermore, water resources management is a highly dynamic and adaptive endeavour in the sense that new technologies, economic instruments, institutional and legal changes, and demand management measures are constantly being introduced, tested and employed as water scarcity becomes a chronic problem (Frederick 1992). Hence, the various strategies outlined in the Resource Use and Management Subgroup of the IPCC Response Strategies Working Group III (1990c) are largely in place or are being implemented in most of the developed countries.

For a number of existing water management systems, comprehensive estimates have been developed, as examples of potential climate change effects on water consumption and use, socioeconomic and ecological consequences of global warming and changes in hydrological characteristics. Few comprehensive and detailed water management studies (as opposed to hydrologic sensitivity analysis) have been conducted, employing the full range and hierarchy of models required for such an undertaking. Among the better studies are those of Kirshen and Fennessey (1992); Lettenmaier and Gan (1990); Lettenmaier et al. (1990); Lettenmaier and Sheer (1991) and Fiering and Rogers (1989).

Two studies (Lettenmaier and Gan 1990; Lettenmaier and Sheer 1991) explicitly modelled large managed river

basins in California, wherein hydrologic simulation models were coupled with snowmelt and soil moisture accounting models developed by the US National Weather Service. The studies used GCM outputs and stochastically created 100 years of rainfall and temperature records from 30 years of historic data. Snow accumulation, ablation and runoff were the primary variables of concern. The response of all four catchments to changed climate conditions were dominated by temperature-related changes in snowmelt and were relatively unaffected by GCM-predicted rainfall changes. Reservoir system performance for the Sacramento-San Joaquin River basin was analysed using the hydrologic information. While the average annual runoff did not change markedly, the shift in seasonal runoff to the winter months had a large impact on the reliability of water deliveries to the various water supply users and on the flood control capabilities of the system.

Two conceptual studies for sizing the optimal capacity and developing ideal operating rules for the design of hypothetical reservoirs under climate uncertainty were undertaken by Fiering and Rogers (1989) and Lettenmaier et al. (1990). Both studies attempted better to understand the vulnerability, resilience and robustness of reservoirs and managed systems under climate uncertainty as a way of improving the design of new systems and operation of existing systems. Essentially both studies confirmed an intuitive notion, that water supply performance, ie the minimisation of shortages or failures (or maximisation of reliability) is controlled more by reservoir storage capacity than by any variation in operating policy. Lettenmaier and Gan (1990) varied reservoir capacity from 0.25 to 0.50 of mean annual runoff. Fiering and Rogers (1989) showed that reservoir reliability did not change much with changes in the climate-induced variation in runoff if the reservoir capacity was larger than 0.5 of the mean annual runoff.

As a whole, the studies on water resources and water management effects of climate change allow the corroboration of the following inference: under the condition of global warming and a great uncertainty of local climate variability, large water management systems are capable of greater flexibility in adapting to changes in timing and magnitude of runoff. In this connection, the watersheds with a large degree of control over river runoff under global warming would have considerable advantages for redistributing the available water supply and flood control compared to the regions with natural unregulated runoff regimes.

## 5 Conclusions

Since the publication of the IPCC First Assessment Report, several studies on impacts of climate change on hydrology and water resources have been conducted. Unfortunately, there is not yet adequate information on regions affected by aridity and desertification and an effort should be undertaken to fill that gap. The new studies expanded the geographic scope of the original surveys, while confirming many previous conclusions; but few new insights were offered on hydrologic sensitivities and vulnerability of existing water resources management systems.

The principal conclusions suggested by the new studies are:

- *Significant progress has been made in hydrologic sensitivity analyses in developed countries, yet large gaps exist in the information base regarding the implications of climate change for less developed nations;*
- *Comparative sensitivity analyses that rely on existing GCMs offer generic insights regarding the physical hydrologic effects and water resources management impacts, but the differences in the outputs of the GCMs coupled with large differences in hydrologic sensitivity analyses makes it difficult to offer region-specific impact assessments;*
- *Temporal streamflow characteristics in virtually all regions exhibited greater variability and amplification of extremes, with larger flood volumes and peak flows as well as increased flow episodes and a shift in the turning of the seasonal runoff;*
- *The higher the degree of water control, regulation and management of sectoral water demands, the smaller the anticipated adverse effects of global warming. Conversely, unregulated hydrologic systems are more vulnerable to potential hydrologic alterations.*

The principal recommendations are:

- *Increased variability of floods and droughts will require a re-examination of engineering design assumptions, operating rules, system optimisation and contingency planning for existing and planned water management systems;*
- *More studies on hydrologic sensitivity and water resource management vulnerability need to be directed towards arid and semi-arid regions and small island states.*
- *A uniform approach to the climate change hydrologic sensitivity analyses needs to be developed for comparability of results.*

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## **Vulnerability to sea-level rise**

The work carried out under this task is discussed under the headings of:

World oceans and coastal zones: ecological effects

Terrestrial component of the cryosphere

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## VII World oceans and coastal zones: ecological effects

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# VII World oceans and coastal zones: ecological effects

## 1 Regional ecological impacts of climate change

Since the IPCC Impacts Assessment (IPCC 1990a) new information has become available that allows existing ideas about regional features and ecological consequences of climate change to be worked out in greater detail. Because of their contrasting natures, the effect of rises in temperature on arctic/subarctic ecosystems are discussed first, emphasising the Bering Sea and the wider Caribbean region as examples. The impacts of sea-level rise on these and Southeast Asian marine ecosystems are then discussed, followed by a summary of the new findings on UV-B, leaching, storm frequency impacts, coastal structures and carbon flux. Finally, there are recommendations for future research, monitoring, database management and for procedural actions. It is noted at the outset that the marine environment and ecosystems are very complex. There are many self-regulating mechanisms that render it difficult to make definitive statements about impacts. Also, from the human point of view, there will be both positive and negative impacts.

## 2 Impacts of rises in temperature

### 2.1 Arctic and subarctic region

The earlier IPCC Impact Assessment provided information on expected physical changes in arctic and subarctic region systems. More physical and biological information is now available. Even the IPCC scenario for climate warming and the attendant reduction in the ocean ice cover may cause a more than tenfold increase of carbon influx in the Eurasian and Canadian basins of the Arctic Ocean to  $1.4 \times 10^9$  kg C/year. This can be compared with the general anthropogenic emission of CO<sub>2</sub> to the atmosphere of  $5 \times 10^9$  kg C/year. In the Bering Sea, for example, the IPCC scenario, along with the intensification of continental and shelf ice melting, will lead to significant increases in river inflow, an average salinity decrease by 0.5–1.0 part per thousand (with greatest reductions in nearshore Alaskan waters), increased turbidity with more suspended particles, a shift northward of surface isotherm of more than 50 km per 0.5°C rise in temperature, and an alteration of the oceanic current system as a result of changes in river flows.

An increase of the vegetative season duration by 1–2 weeks should lead to an annual primary production increase of 5–10%, with an increase of 1.2% in secondary production, elimination of 8–12% more organic matter from the photic layer through biosedimentation, and bacterial decomposition of organic matter will increase. It is estimated that the minimal increase in absorption of

atmospheric CO<sub>2</sub> by the Bering Sea each year will grow from about  $50 \times 10^9$  kg C/year to about  $62 \times 10^9$  kg C/year.

A temperature rise of 1.5–2.0°C in the deep water part of the Bering Sea will not result in a significant rise in the phytoplankton photosynthesis rate, but the intensity of microbiological processes and the organic matter decomposition rate may increase significantly. As a result, the production-destruction coefficient (P/D) is expected to decrease, especially during late spring and summer.

The combined effect of temperature rise, pH decrease, pollutant concentration increase, and the strengthening of imbalance of organic compounds production and destruction between different ocean regions, will lead to changes in marine ecosystems. The ice regime plays an important role in the life cycles of the inhabitants of the sea beginning with micro-algae and finishing with the great whales. Ice cover reduces light in the Bering Sea, the biomass of micro-algae directly under the ice is two to three times less than in waters free of ice. After ice thawing, mass development ('blooms') of phytoplankton begins in surface water layers, followed by rapid population increases of zooplankton which serve as food for some fish, birds and mammals.

A shift of the main oceanic currents should be expected even with a relatively small change in the mean temperature of the order of 2–4°C and river inflow increases. It is obvious that in this case the system of circulation, to which the life cycles of commercial species of fish and invertebrates inhabiting the coastal and especially seamount regions are 'tuned', will be disturbed. In these cases, decreases in reproduction and even disappearance of specific populations can be expected. Different species may eventually move into these areas and the mix of species may be different. These changes occur under natural climate variability, but could be accelerated or become more intense under the IPCC scenarios.

Changes in transparency, water colour, current speed and direction, and other parameters will affect the function of ecosystems. For instance, enrichment of coastal waters in biogenic elements will lead to an increase in the primary production of phytoplankton and macrophytes, while increased water turbidity may cause a reduction in the depth of the photic layer and therefore a loss in productive water volume. Water warming and enrichment with organic matter will increase the activity of microbial populations and will intensify the decomposition of organic matter. Climate change will have different impacts on fish species, depending on their ecological features. The most vulnerable species are those fish and invertebrates dwelling in the coastal waters. However, the species dwelling in the seamount regions of the open ocean may also be strongly affected.

The larval stage is the most vulnerable in the development of fish (Bernal 1991). Larvae of oceanic species are less subject to negative consequences than those of coastal species, although slight changes in temperature and salinity may widen or limit the regions where successful survival of larvae is possible. A change in salinity will strongly affect the larval stages of coastal species, for instance, of valuable commercial species. Some cases of increased mortality of marine organisms resulting from sea-water freshening have been noted. Further, it is not clear how recent findings of increasing UV-B irradiance will affect high-latitude marine ecosystems, but there are potential negative impacts on near-surface plant and animals and particularly on fish eggs and larvae.

A change in ice conditions will affect the dynamics of populations of high-latitude fish species. Earlier melting of ice will lead to the lengthening of growing periods and ultimately, to an increase in the biomass of populations. Further, a shift of some boreal fish species northward is expected, following the ice edge, where accumulations of such species as cod are observed.

## 2.2 Tropical/subtropical regions

Temperature change is only one aspect of the climate that will affect terrestrial and aquatic ecosystems. Hanson and Maul (1992) find no evidence for changes in precipitation in Florida during the last 101 years; similarly Aparicio (1992) finds none along the southern Caribbean. In the central Caribbean region, Gray (1992) finds decreased rainfall in the last 20 years, which he associates with decreased hurricane activity. An increase of 1.5°C in sea surface temperature could increase the number of hurricanes by as much as 40% (Shapiro 1988), and the maximum wind speed by 8%, all other things being equal. Shapiro is quick to point out a considerable uncertainty in these figures (40% increase means on average  $+1.6 \pm 1.2$  hurricanes/year). Many other factors are important in hurricane analysis, and it may be that the storm formation location and track are more important than changes in strength or frequency.

In the sense that Lamb (1987) develops climate change scenarios as plausible future events, Gray (1992) argues for the following likely effects (cf Gallegos et al. 1992; Aparicio 1992; Wigley and Santer 1992): rainfall will continue to decrease, air temperatures will continue to rise, surface wind speed will continue to increase, and evaporation will increase. Caution must be exercised in interpreting these changes as anything other than 'persistence forecasting'. It is not known, for example, if the decreased frequency of large hurricanes over the last two decades is really a long-term trend or part of some cycle as yet not understood. Hurricanes are an important contributor of

rainfall; is the decrease in precipitation merely a reflection of fewer large storms? Increased temperature may affect the drag of wind on water, but Mercado et al. (1992) and Hendry (1992) see no clear indication of significant change in storm surges or waves associated with elevated temperature.

In the tropics, marine organisms live closer to their maximum thermal tolerance than those in more temperate climates (Vicente et al. 1992). Although the 1.5°C temperature rise scenario would raise the summertime mean temperature to 30.5°C over much of the tropical/subtropical region, most migratory organisms are expected to be able to tolerate such a change. Some corals will be affected (viz the 1983 and 1987 bleaching events), but it is expected that other environmental stresses will be more important (Milliman 1992). Intertidal plants and animals, such as mangroves, are adapted to withstand high temperature, and unless the 1.5°C increase affects reproduction, the rise in temperature will probably cause unmeasurable results (Snedaker 1992). Similarly, only seagrass beds already located in thermal stress situations (ie in shallow lagoons or near power plant effluent) are expected to become negatively affected by the projected IPCC (1990b) temperature rise.

The blue, clear waters of tropical/subtropical regions are relatively poor in nutrient. It is not expected that a modest increase in temperature will significantly affect the fisheries except in some shallow lagoons where salinity may affect productivity, particularly if juvenile organisms have a critical dependence on salinity or temperature. Increased alongshore winds, however, could lead to increased coastal upwelling along some continental coasts (Aparicio 1992), or to other oceanic circulation changes, (Gallegos et al. 1992), and thus to increased productivity (cf Vicente et al. 1992).

Tropical fish eggs hatch very quickly (12–18 hours), and development is associated with temperature. Just as 'cold snaps' can be devastating, so can 'hot snaps', particularly during early juvenile stages. Extremes in temperature are usually averaged out in climate analysis, but with increased temperature, the likelihood of 'hot snaps' increases; the 1987 Caribbean coral bleaching event is attributed by some researchers (Williams et al. 1987) to 'hot snaps'. The complexities of the ecosystems could be greatly affected by slight temperature changes. It is not known, for example, why fish stocks either decline or increase by orders of magnitude, other than owing to early life history events caused directly by the physical environment or indirectly through complex chains in ecosystems dynamics. Temperature effects on tropical fisheries, as for those in other latitudes, remains an important and unanswered question, although there is some evidence of fish migration associated with increased coastal temperatures.

### 3 Impacts of sea-level rise

#### 3.1 Bering Sea

One of the most important aspects of climate change is the impact of the predicted (IPCC 1990b) sea-level rise on coastal and marine ecosystems. The ecological situation will change, the life cycle of many organisms will be disturbed, and a decrease in the habitat of sea animals and/or their redistribution will occur.

The predicted rise in sea-level will result in moderate impacts by 2050, growing to serious impacts in 2100 and beyond. The projected sea-level rise will change the ecology in many areas of the Bering Sea. The most significant effects will be in areas where there are high densities of animals and a strong tendency for transformation of the shore. The consequences for the Bering Sea, one of the high-production regions of the World Oceans, may be very important. Numerous marine mammals and birds are located on seashores—narrow coastal land bands, lower islands and individual rock debris. The nursery areas of some valuable fish species are located in the shallow water deltas of the Bering Sea rivers. Sea-level rise will reduce the size of the habitat of numerous birds, mammals and fish. The sea-level rise will also affect the distribution of plant life along the Bering Sea shores, particularly the *Fucus* type algae inhabiting the depth down to 0.5 m. These algae will partially or completely die off or be replaced by others.

#### 3.2 Caribbean/Gulf of Mexico/Bahamas region

Relative sea-level rise is the net effect of tectonic uplift or subsidence, eustatic change due to continental ice melt, winds and ocean currents, plus expansion or contraction of the water column. During the Holocene (last 10 000 years) in Jamaica, for example (Hendry 1992), maximum sea-level rise is 0.27 cm/year, or less than half the 0.6 cm/year implied by the IPCC (1990b); in the last 3000 years sea-level rise has been almost nil. All other things being equal, 0.6 cm/year (35 cm between 1990 and 2050) is expected to place an unusual stress on coastal ecosystems. Climate change involves much more than sea-level rise and temperature increase; precipitation, evaporation, humidity, wind velocity, hurricanes, cloudiness, solar irradiance, ocean currents, waves, mixing, riverine input etc, are all important variables. If precipitation changes (for example) are markedly underestimated, the impact on agriculture and coastal ecosystems could be far more important than sea-level and/or temperature rise.

The second largest coral reef system in the world dominates the offshore area of the western Caribbean Sea (Milliman 1992), and all but the northern Gulf of Mexico

coast has extensive reef systems. Growth of individual coral organisms is estimated between 1–20 cm/year (Vicente et al. 1992) and reef growth rates as a whole are known to be up to 1.5 cm/year (Hendry 1992). Not all reefs accumulate at these rates but, if they did, they could keep pace with the rise in sea-level of 35 cm by 2050 if other factors do not alter growth conditions. Environmental stress on the reefs from other variables (storms, sedimentation, disease, rainfall, radiation, turbidity, overfishing, mass mortality in algal grazers etc) may prevent some from keeping pace with rising sea-level, resulting in alteration of the nearshore hydrodynamics. The issue is further complicated by consideration of the type of reef, coastal geomorphology, reef depth and ecological state of the reef in question. Accurate predictions on the effect of sea-level rise may be possible in reefs that have already been physically and biologically monitored, such as in Panama, Jamaica and Puerto Rico.

Mangrove forests are a unique feature of protected coastal shorelines of the tropics and subtropics; their root systems (prop roots and pneumatophores) stabilise the sediment, dampen wave energy, provide habitat shelter for numerous organisms and form the basis for the nearshore marine food web (Vicente et al. 1992). The five species comprising the mangrove flora of the Caribbean/Gulf of Mexico/Bahamas region occupy an area of approximately 3.2 million hectares, or some 15% of the estimated world area of mangrove of 22 million hectares. The best developed mangrove forests are associated with areas of high precipitation and upstream runoff. Thus, in terms of global climate change, future changes in patterns of precipitation and runoff will have impacts on mangroves (Snedaker 1992). Mangroves grow best in moderately saline environments where the rate of peat production exceeds the anaerobic decomposition of peat by marine sulphate reducing micro-organisms, and by this process, low-island mangroves could keep up with sea-level rise of up to 12 cm/100 years. Mangroves of high islands and continents also accumulate sediment from river discharge, hence can keep up with higher rates of sea-level rise (Ellison and Stoddart 1991). The current high rate of regional mangrove loss by overcutting, land clearing and habitat conversion suggests that global climate change is a minor factor in considerations of the fate of this regionally important coastal habitat.

Seagrasses are a benthic environment throughout the tropical and subtropical regions that are important in stabilising bottom sediments, serve as nurseries for juvenile organisms and provide surfaces upon which many organisms attach. A 35 cm sea-level rise per se is not expected to affect seriously the six common Caribbean region species (Vicente et al. 1992), but if there are other changes, such as in the quality of light, influence of herbivores,

substrate, wave energy, or bottom slope, the seagrass beds may be impacted.

The impact of sea-level rise on fisheries is not expected to be great unless turbidity increases due to erosion from higher water or river runoff. Turbidity increase could have a negative impact on fisheries particularly during the early life history stage (W Richards, NOAA/ NMFS, personal communication). Estuarine-dependent species in areas such as Mississippi, the Florida Everglades, Guyana and the Orinoco Delta, may be particularly vulnerable to sea-level rise, especially if salinity changes are involved.

### 3.3 Southeast Asia region

Parry et al. (1991) reported on potential effects of climate change for Brazil, Malaysia/Thailand/Indonesia and Vietnam, but did not discuss sea-level rise for Brazil. Much of the area of Malaysia/Thailand/Indonesia is characterised by low-lying coastal plain where a 35 cm rise in mean sea-level will lead to a shoreward advance of seawater of almost 1 km. On sandy beach coasts, sea-level rise would tend to initiate beach erosion or accelerate it where it is already taking place. There are large areas of swampy lowland in Southeast Asia, especially on the shores of deltas, where sea-level rise will tend to curb the accreting coasts.

The natural vegetation associated with the coastal lowlands of Southeast Asia is mangrove swamp backed by marshes and areas of freshwater forest. In many areas this vegetation has been profoundly modified by drainage and land reclamation. Extensive areas of mangroves have also been converted to ponds for the production of fish or prawns. Where mangroves have been converted to mariculture, sea-level rise will threaten to breach the enclosing banks and submerge the mariculture ponds. Coral reefs on the other hand have growth rates (as with the Caribbean) that can keep up with sea-level rise, except fringing reefs, which are less likely to survive than outlying reefs, because of increased turbidity in coastal waters.

As with all of Southeast Asia, Vietnam (Parry et al. 1991) has experienced erosion of mangrove forests where their advance inland has been prevented by agricultural development. On balance, Vietnam has experienced an increase in the production of mangroves due to sea-level rise. Fisheries on the other hand are mostly influenced by areas of coastal upwelling, and climate change may act more to displace these traditional fisheries rather than to change their productivity. The potential effect of possible increases in typhoons and the prolongation of the typhoon season is perhaps the severest uncertainty affecting the coastal region of Vietnam with climate change.

### 3.4 Summary

We summarise the effects of sea-level rise for three regions in Table 1. These levels of vulnerability reflect only the IPCC (1990b) climate scenario, and must be considered as issues that exacerbate other problems such as population pressure, pollution, subsidence, coastal erosion, construction, warfare etc and is presented to open discussion on identifying the most vulnerable ecosystems.

We also note that a healthy environment is a prerequisite for coral reefs, mangroves and sea grasses to keep pace with a rising sea and to continue their coastal protection benefits.

## 4 Case study areas in progress

Some 29 country studies have been completed or are in progress for Africa (5), Asia (10), Australia (1), North and South America (9) and Europe (4) regarding vulnerability to sea-level rise, including ecological impacts. For example, using video-mapping techniques to capture the natural and human dimensions of the coastal zone in Senegal, scientists have projected a loss of 6000 km<sup>2</sup> of wetlands and dry land. Similar studies using this technique have been completed or are in progress in Argentina, Nigeria, Uruguay, Brazil and Venezuela (Dennis, et al. 1991). Six regional studies on Implications of Climate Change have been organised by UNEP: the Mediterranean, Southeast Pacific, South Pacific, East Asian Seas, South Asian Seas and the Wider Caribbean Region. Each area has unique problems, but each shares the common concern of changing air and water circulation, coastal geomorphology, coastal ecosystems, soil degradation, freshwater resources, precipitation patterns, terrestrial ecosystems, coastal industries and settlements, and littoral zone population dynamics. The underlying thread often emphasises negative aspects of climate change; this is not necessarily universal. Whenever established patterns are disturbed, vested interests tend to exhibit a concern. Rising sea-level is probably of more concern than rising temperature, but it is too early to be definitive; this is the dilemma that any forecaster must confront.

## 5 Recent findings and updates

### 5.1 Ultraviolet (UV-B) radiation

The IPCC Impacts Assessment expressed concern about the possible effects of increasing irradiance of UV-B on marine ecosystems. New findings of the WMO/UNEP (1991) indicate that UV-B radiation reaching oceanic and coastal zone environments will increase faster than expect-

ed. Since so many marine resources spend all (or vulnerable parts) of their lives near the water surface, the urgency of our concern over genetic changes and direct harm to plant and animal life is heightened accordingly.

Solar radiation bleaches cellular pigments of freshwater and marine phytoplankton and also impairs motility and photomovement of the plankton. The marine phytoplankton communities represent by far the largest ecosystem on earth. Therefore, even a small percentage decrease in population would result in important losses in the biomass productivity of the ocean. Any decrease in the phytoplankton populations will decrease the sink capacity for atmospheric CO<sub>2</sub> and will change the carbon biogeochemical cycling in the marine environment.

### 5.2 Coastal contamination

The 1990 assessment also expressed concern about the leaching during sea-level rise of contaminants from coastal sewerage and toxic waste disposal sites in nearby human population centres and agricultural regions. It has been brought to our attention that there are also bacterial and viral agents in such sites and in coastal septic sewerage systems which could be increasingly released into coastal waters. While there are potential impacts on coastal resources (including nutrient loading of confined water bodies, (Valiela and Costa 1988)), the primary concern is for the human populations who consume the resources and the loss of commerce caused by the closure of fish and shellfish areas by health authorities.

### 5.3 Storm intensity/frequency

In regions of small tidal range such as the Gulf of Mexico, there are wetlands that are found above the high-tide line which become inundated by meteorological forcing (storm surge/frontal passage) or far field oceanic forcing (Swenson and Chuang 1983). These high intertidal wetlands are important in supporting marine resources. In the Gulf of Mexico, moving inland from the coast, the tidal signal gets damped more effectively than does the meteorological/far field signal. These interior inundation events can impact shrimp harvests (Childers et al. 1990). Depending on the particular site, changes in storm frequency or intensity could have positive or negative impacts on marine resources.

### 5.4 Coastal structures

The assessment that most wetland loss accompanying sea-level rise would be due to inundation and not to protective

coastal structures is reaffirmed; it is also recognised that much of the inundation effect could be an indirect result of structures built to combat coastal sea-level rise (Hendry 1992; Parry et al. 1991). For example, the construction of weirs to prevent saltwater intrusion into wetlands, or the construction of levées along rivers/wetland boundaries to prevent flooding, can lead to impounding of water, development of anaerobic conditions and sulphide build-up in marsh soil which can be accompanied by the death of the wetland vegetation and land loss (Mendelssohn and McKee 1988). The weirs accomplish this by directly controlling water levels, while the levées can achieve the same result from backwater flooding. Weirs can also prevent the movement of living marine resources from wetland nurseries into the adjacent coastal waters (Knudsen et al. 1989).

## 6 Research and monitoring needs

Several important research needs were identified during the preparation of this report. These are discussed below, by subject areas, to help guide the setting of research priorities.

### 6.1 Monitoring

Develop a global scale, coordinated program of monitoring and analysis and use retrospective records to understand past environmental changes and their effects on coastal communities. This is needed to identify and understand synergetic stress factors and to use these measurements as potential indicators of climate change. In particular, support the IOC/WMO/UNEP co-sponsored Global Ocean Observing System (GOOS) by active participation in the program.

### 6.2 Methods

- Develop methods to build a framework of modules, integrating physical, biological, and human dimensions, which will lead to better understanding of the ecological consequences of climate change.
- Prepare regional maps with a classification scheme showing areas and ecosystems most vulnerable to climate change.

### 6.3 Ultraviolet-B radiation

- Determine the susceptibility of marine organisms to increasing amounts of UV-B radiation and the quanti-

tative impacts of these effects on marine ecology, on fisheries and on marine carbon cycling;

- Monitor UV-B at ecologically important sites at all latitudes.

#### 6.4 Modelling

- In order to strengthen quantitative information transfer to states, regional climate models nested in coupled ocean-atmosphere global circulation models are needed. This effort must include a vigorous, stable, long-term in situ verification program (such as GOOS), coupled with an active multi-disciplinary research effort, which should include examination of the historical, geological, and archaeological records.
- Numerical socioeconomic model development, validation, transfer and use training should be initiated. This new class of models require customisation for individual nations/regions. Adequate database development must progress in parallel with the model development. Coastal zone managers will require modest training and this should be given high priority within IOC/WMO/UNEP education programs.

#### 6.5 International programs

- National and regional research institutions are urged to combine forces in order to develop comprehensive studies of the interactions of marine biological communities with their environment and to determine how these relationships will change with a changing world. It is noted that several such studies are under way (regional, north-south, centres for global change research, for example.)

#### 6.6 Ecological research

- Undertake sufficient research on trophic pathways and carbon cycling to understand predator/prey, plant/animal, chemical/physical, and organism/environment interaction as a foundation for understanding the effects of global change on the marine environment and vice versa.
- Study the linkages of climate dependent sea surface momentum and energy exchanges to marine ecosystem processes and populations of economic or cultural interest.

### 7 Recommendations

- Implement the research/monitoring needs in the above section.
- Strengthen interaction of this working group with the Coastal Zone Management Subgroup of IPCC Working Group III—Response Strategies.
- Response Strategies (WGIII) should fully consider the impact of coastal structures on inland retreat and on flushing action required by coastal ecosystems.
- Add Climate and Global Change to the agendas of appropriate future meetings of regional scientific and coordinating bodies such as IOC, WMO, UNEO, UNDP, FAO, IMO and others; appoint a regional IPCC coordinator responsible to the Secretariat.
- Coastal planners and owners of coastal properties and infrastructure should carefully consider projected relative sea-level changes when evaluating new or reconstruction projects.
- Coastal planners and environmental decision makers should consider that a healthy environment is a prerequisite for coral reefs, mangroves and sea grasses to keep pace with a rising sea and to continue their coastal protection benefits.

Table 1. Effect of 35 cm sea-level rise by 2050 AD\*

- (L) = Low impact  
(M) = Medium impact  
(H) = High impact  
(-) Not applicable

	Ecosystems		
	Tropical/ Subtropical	Mid- Latitude	Polar/ Subpolar
Deltas	H	H	H
Estuaries	M	M	M
Wetlands	M	M	M
Coastal plains	M	M	L
Coral reefs	L	H	-
Lagoons	M	M	M
Mangroves	H	-	-
Ice margin	-	L	M
Seagrass beds	M	M	L
Fisheries	M	M	L
Rivers	L	L	L
Coastal lakes	L	L	M
Beaches	H	H	H

\* This table only considers the rise in sea-level and is not intended to include the numerous environmental stresses that these ecosystems are experiencing from other local anthropogenic effects.

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## VIII Terrestrial component of the cryosphere

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# VIII Terrestrial component of the cryosphere

## 1 Background

The terrestrial component of the cryosphere includes the seasonal snow cover, mountain glaciers, terrestrial ice sheets, frozen ground including permafrost (ground that remains frozen for more than one year) and seasonally frozen ground. In conjunction with projected changes in climate associated with enhanced atmospheric concentrations of greenhouse gases, the global areal extent and volume of these elements of the terrestrial cryosphere are expected to be substantially reduced (Climate Change: The IPCC Impacts Assessment, 1990). These reductions, when reflected regionally, could have significant impacts on related ecosystems (both natural and managed) and on social and economic activities. For example, the projected reductions in the area and volume of seasonal snow cover (including changes in the length of the season) and the recession of glacial ice sheets will impact on local and regional water resources. In the case of permafrost, projected increases in the thickness of the freeze-thaw layer above the permafrost and recession of permafrost to higher latitudes and altitudes could lead to increases in terrain instability, erosion and landslides in those areas which currently contain permafrost. These changes could alter overlying ecosystems and affect existing human settlements (structures) and development opportunities.

The study of the impacts of climate change on the terrestrial components of the cryosphere is in its infancy and there are many uncertainties regarding the relationships and sensitivities of snow and ice masses to climate and climate changes especially at the local and regional levels.

Limitations also exist in terms of our understanding of the environmental impacts (Koster 1991) and of socio-economic consequences of changes in snow and ice masses. Addressing these uncertainties and limitations is essential to the development and implementation of appropriate response strategies.

## 2 Progress since the IPCC Impacts Assessment in 1990

### 2.1 Snow cover

Recent analyses (Cess et al. 1991) of the differences in the behaviour of General Circulation Models (GCMs) suggest that snow feedbacks include both the simple, direct positive feedback and indirect negative affects. The positive feedback hypothesis suggests that a decrease in snow cover makes the earth less reflective, causing it to warm as it absorbs more solar radiation and reflects less back out to space. Recent analyses reveal that some models suggest

that clouds could redistribute themselves to cover those areas which were covered with snow thus reducing to some degree the positive feedback. Some of the models also suggest that decreases in snow cover could increase the amount of long-wave radiation emitted at the top of the atmosphere, which would lead to cooling of the Earth.

Robinson and Dewey (1991) examined a 20-year data set of satellite derived snow cover and found the extent of northern hemisphere snow to be at record low levels since the middle of 1987. The largest negative snow anomalies of late are occurring in the Spring.

Meteorological data gathered along the Mackenzie Valley in Canada over the past 50 years shows a long-term warming trend of up to 1°C (Stuart et al. 1991). Analysis of this data shows that along with this increase in air temperatures, snow cover has decreased in the Mackenzie Valley. Under this combination of climatic changes permafrost could grow, not diminish, in this region (Stuart and Judge 1992).

### 2.2 Permafrost

The raising of mean annual air temperatures by 2°C is projected to result in a shift of the southern boundary of permafrost areas in Russia approximately 250–300 km to the north and northeast. A warming of this magnitude is also expected to cause the receding of permafrost areas on the plateaus of Tjyan Shan and the vanishing of those in Pamir with only spotty discontinuous areas remaining. Based on mathematical models, permafrost could lose 2–6% of its 'cold reserves' during the period 1990–2040 as a result of projected global warming.

The above normal temperatures throughout much of the Northern Hemisphere in 1989 led to the initiation of extensive active layer detachment slides in Ellesmere Island, Canada, and in the Yamal Peninsula in the Russian Arctic. A thicker active layer intersected the top of massive ice triggering the failures which are continuing to spread in these areas. This condition, at least in the Yamal Peninsula, has led to the damming of streams, increased sediment loads in streams, and has initiated ongoing thaw and further failures.

Allen et al. (1988) have identified the growth and decay of permafrost in the Mackenzie Delta, Canada, over the past 75 000 years based on deep temperature records and the palaeoclimatic history. Rozenberg et al. (1985) have documented multilayered permafrost in the Mackenzie Delta, and Collett et al. (1988) have shown a similar structure over several thousand km<sup>2</sup> on the North Slope of Alaska.

Anisimov and Nelson (1990) and Stuart and Judge (1992) have used the frost index model to examine the

circumpolar distribution of permafrost and to compare it for Eurasia and Amerasia. The advantage of the frost index is that it accounts for and couples both temperature and precipitation (snow cover). Further calculations have examined the change as predicted by the various GCMs.

Field studies using deep temperature records from boreholes (Taylor et al. 1989 and Taylor 1991) have demonstrated that recent sea-level changes in the arctic are preserved in these temperature records and that these temperatures can be used to estimate the retreat or advances of shorelines.

Studies of the isotope chemistry of carbon in the atmosphere suggests that up to 30% derives from old carbon (or earth) sources. In the tundra and northern taiga ecosystems there is an abundant reserve of carbon stored in moss, peat, and soil duff. The potential release of this carbon as a result of global warming and the associated increase in soil temperatures, increasing depth of the seasonal thaw layer, and improved drainage suggest increases in CO<sub>2</sub> emissions from these regions as a result of global warming. Currently, CO<sub>2</sub> data from global systematic observations identifies a maximum of annual mean CO<sub>2</sub> concentrations over the tundra and northern taiga regions around 70°N latitude and not between 20–60°N where the greatest majority of the emissions from human activities occurs.

Recent experiments indicate that a sharp increase in CO<sub>2</sub> emissions from deep freezing soil monoliths occurs by warming them 4°C. This conclusion is supported by the increase in emissions that is observed in April as the temperature of the upper horizon of frozen deposits increases from -8°C to -4°C.

Emissions of methane from the earth's surface are currently estimated at 540x10<sup>12</sup> g/year including 35x10<sup>12</sup> g/year from tundra areas (Khalil and Rasmussen 1990 and Melnikov 1991). The annual flow rate of methane into the atmosphere from present-day sources within permafrost regions in Russia are estimated to be 9.2x10<sup>7</sup> m<sup>3</sup> or 6.1x10<sup>4</sup> tonnes (Glotov, in press).

The amount of methane within permafrost has not been extensively studied (examples of some studies, Archangelov and Novgoroda 1991 and Kvenvolden et al. 1992) with the majority of studies having been carried out in oil and gas fields for which methane is the target indicator. Recent investigations in Kolimo-Indigirka lowland area, have found methane in borehole samples at concentrations from 3.2 to 63.7 ml/dm<sup>3</sup> with the greatest concentrations in the turl-organic horizons. It appears that the stable zone of gas hydrate deposits in permafrost lies more than 100 metres below the surface where the temperature are between -10°C to -12°C.

In some regions of the arctic there is evidence which suggests that the continental shelves are warming as

permafrost degrades. In the Canadian Beaufort Sea, shallow sediments are very gassy and several plumes emerging from the Russian shelves have been attributed to sudden emissions of methane due to hydrate degradation. Such emissions may themselves contribute to climate change in the short term and may indicate a trend towards accelerating hydrate decomposition on northern shelves. Climate warming accompanied by shelf warming as a consequence of increased meltwater input will accelerate this decomposition (Neave et al. 1978; Clarke et al. 1986; and Nisbet 1990).

### 2.3 Ice sheets

Some glacier-mass budget record lengths are now sufficient to be useful as a climate change indicator tool, having reached or exceeded the 'thirty-year norm' criteria. They can therefore serve as a background to test the climate change projections over broad areas. For example, there is good evidence now (Koerner and Brugman 1991) that glaciers in the Northern Hemisphere polar and subpolar regions are receding at a slower rate than previously suggested. In addition, all glaciers measured in Iceland between 1930 and 1960 were receding. Between 1960 and 1990, however, 25% have advanced.

The longest glacier record from northern Sweden identified only eight positive balance years between 1946 and 1980. In the ten years since then, six years have shown a positive balance. In the Canadian high Arctic (Koerner and Brugman 1991), thirty years of mass balance on two ice sheets show slightly negative balances with no significant trends. This evidence, which is substantial, is the opposite to that found from two years of similar measurements taken earlier—one in the 1970s and the other in the 1980s.

Observations from Kazakhstan (High Mountain Geocryological Laboratory) indicate that between 1955–1979 the glaciated area reduced by 13.7%, the number of glaciers diminished by 15.2% and the general volume of ice in glaciers reduced by 10.8%. During the same period, the volume of water flow from the glaciers increased from 295 to 340 billions m<sup>3</sup> annually (ie 15% increase). Continuing this rate of glacial ablation would suggest that the glaciers in Zailiisky Alatau would vanish over the next 200 years.

Although the Southern Hemisphere record is not as detailed as that for the Northern Hemisphere, work by Ruddell (1990) has shown that several New Zealand glaciers have retreated since the mid 1800s. In particular, a decrease in the volume of the Tasman Glacier is attributed to a warming in the order of 0.75°C, accompanied by

a decrease in precipitation of about 10% since the middle of the last century.

### 3 Information and data gaps

In addition to those uncertainties associated with climate change (IPCC 1990), the limited state of knowledge and understanding of the sensitivity of polar and high-altitude regions, especially with respect to climate change, is restricting our capabilities to estimate the environmental impacts and therefore, socioeconomic consequences, of climate change as a result of changes in these components of the terrestrial cryosphere. Despite the large volume of literature, there is a limited number of accessible relevant datasets for scientific research. Future systematic observations and associated research should give priority to designing and implementing programs to provide the necessary data and, thereby, to increase our understanding of:

- basic cryospheric processes and phenomena;
- slope processes and mass movements;
- the emission and storage of carbon by polar and high-altitude ecosystems; and
- the associated changes in vegetation and wildlife community structures and functions.

With respect to permafrost, causes of changes in ground temperature profiles need further theoretical and field study to provide greater insight into when permafrost degradation will begin, at what rate it will occur and to what depth.

GCMs do not adequately incorporate atmospheric and cryospheric energy fluxes for polar regions encompassing vegetative terrain, snow cover, and ice sheets, with the complications of freeze/thaw. The coupling between the atmosphere and the cryosphere is therefore not well represented, leading to uncertainty in projecting the location, timing (including rate) and extent of snow cover disappearance, ice sheet ablation, soil temperature and moisture profiles, soil moisture movement and permafrost degradation.

Current efforts towards systematic observations and examining impacts of global change within the terrestrial cryosphere are not always undertaken in a coordinated fashion. The Arctic, for example, is largely omitted from the IGBP Planning Documents despite the enormous heat storage and release capabilities of the cryosphere. There are programs, however, which deal with many of these shortcomings. For example, WCRP is developing an Arctic Climate System Study (ACSYS) program and efforts are being made by IASC and the US NSF (Arctic

System Science). These efforts and those with similar goals need to be encouraged and strengthened.

The number and areal coverage of long-term systematic observation sites in high-latitude and high-altitude regions are insufficient to provide more than qualitative and theoretical assessments of components of the terrestrial cryosphere and the impacts of climate change on them individually and together. Some such systematic observational efforts have been undertaken for permafrost (eg Mackay in the Mackenzie Delta of Canada, Pewe in the Fairbanks, Alaska, area and research by Pavlov and Melnikov in Russia). Existing observation programs need to be maintained and, where necessary, enhanced to provide the required long-term observation records. Additional sites, however, are required throughout the high-latitude and high-altitude regions. Particular emphasis should be given to addressing data gaps within priority areas, including the main population centres and transportation routes, providing areal coverage to encompass a linear transect through the discontinuous and continuous permafrost, and including areas in which there are major sheets and adjacent terrestrial and marine environments. Every attempt should be made to encourage the operation of these types of programs in a manner that promotes international cooperation and involvement, thereby providing the opportunity for intercomparison.

Comprehensive spatial data that will allow analysis of trends and spatial distribution of elements of the terrestrial cryosphere are especially limited. Remotely sensed data, although not yet fully developed, ultimately should provide the best approach to assessing responses and identifying potential risks over large areas quickly and frequently. A regional example of this type of program is the CRYSYS program developed by USA and Canada. The CRYSYS program has been conceived as a part of the Earth Observation Satellite Programme designed specifically to evaluate the impact of global change on the cryosphere.

As pointed out under the previous section, an important factor in the relationship between climate change and permafrost degradation appears to be the decomposition of marine gas hydrates, which results in the release of radiatively important gases to the ocean and atmosphere. Little is currently known about their distribution, chemistry and kinematics.

Uncertainties exist in our understanding of the relationship between glacier mass balance and climatological conditions. These uncertainties must be resolved to improve estimates of ice sheet ablation contributions to sea-level change and to local/regional hydrological regimes (especially important for those areas which depend on meltwater from the terrestrial cryosphere).

Our knowledge of the effects of the major ice masses on changing sea-level in the event of global warming is

limited as a result of the uncertainties regarding the mass balance of the Greenland and Antarctic ice sheets. In fact, changes in the mass balance of the Greenland and Antarctic ice sheets are not certain even as to sign. A recent compilation of data concerning the Antarctic mass budget (areas of the Antarctic Peninsula have not been included in these calculations) by Bentley and Giovinetto (1991) has, however, concluded that the ice sheet currently exhibits a positive balance (ie an excess mass input) of 80 to 400 Gt/year, contributing a drop of 0.2 to 1.1 mm/year to sea-level change.

With respect to Antarctica, major deficiencies in the knowledge base can be attributed to lack of knowledge of the accumulation rate over most of Antarctica, the basal melting rate of the ice shelves, and the ice calving rate along the entire margin of Antarctica. For the Greenland ice sheet, insufficient information is available about the ablation rate (currently restricted to a few years of measurements at a few points) and the calving rates at the fast moving outlet glaciers (eg Jakobsavn).

These deficiencies make it virtually impossible to relate changes in the global glacier mass balance to sea-level change, either in the past or in the near future. Modelling cannot answer these questions until annual-to-decadal data on the surface profile of both Greenland and Antarctica are available. This data requirement will be realised only if and when the new generation of satellite altimeters are put into orbit some time in the next century. For Antarctica there is an additional need to improve the information available on snow accumulation rates and how they relate to synoptic weather patterns each year.

Historical accumulation data obtained retrospectively from ice cores can provide the perspective on natural accumulation rate variability which is needed to assess the significance of more recent changes. An essential aspect of this as well as other sampling or systematic observation programs, however, is communication of the resulting data or information. One notable shortcoming in this area for Antarctica is that accumulation rates for stations occupied since 1957 still remain unpublished (Jacka 1991, personal communication).

#### 4 Responses to close information and data gaps

The collection, through internationally coordinated programs, of basic data on snow cover extent and volume, glacier behaviour, and permafrost temperatures, ice content and thickness is of utmost importance to improve our understanding and to improve models of climate-cryosphere relationships. Where possible, existing time-series of observations should be compared with recent and historical climate records to study the cryospheric responses

to recent warming and specific climatological conditions. Current observational programs should be continued, while the extension of the global network with observations at new locations (particularly in the Southern Hemisphere) and by remote sensing (eg satellite, radar and photogrammetry) is strongly recommended.

Integrated research should be carried out on the side effects of fluctuations in snow cover, glacier size, and permafrost dynamics on, for example, the stability of slopes, runoff, the supply and transport of sediment, timberline ecotones, food chains, and on wildlife migration.

##### 4.1 Snow cover

The natural variability and trends, if any, of continental snow cover changes is poorly known because of the short length of comprehensive data records (ie satellite observations from the 1970s to the present). To enhance these records, appropriate protocol to integrate surface observations with recent satellite data is needed to expand the temporal coverage. This is required not only for snow cover, but also for the other components of the terrestrial cryosphere.

Specific efforts should be directed at collecting the required data to help identify areal and altitudinal snow cover change trends. The required observation programs include continued systematic observations of snow extent and duration both by field observations and remote sensing, improved observation of snow depth/volume and water equivalent, and collection of data on mountain snow pack characteristics.

Work must also continue on assembling and analysing historic station-based observations of snow cover in order to provide a greater historic perspective to recent snow behaviour without having to wait decades to assemble a satellite set of suitable length. Of course, this can be accomplished only on a regional scale, but even on this scale the work would prove useful.

For remote sensing of snow cover extent and depth/volume, the hope is that microwave satellite data will provide the necessary information. This technique currently shows some promise but still requires some 'tuning' before reliable snow cover volumes can be obtained (eg in boreal forests and over tundra).

Another approach which should be applied to future snow observations employs geographic information systems techniques. These permit the amalgamation of remotely sensed data with traditional ground-based station observations, topographic data, vegetation information etc.

Further research towards understanding the impacts of climate change on regional and hemispheric snow covers

is needed; research is also needed on the impacts of a changed snow cover on the climate system. Relationships between snow cover, surface and upper atmospheric temperature, precipitation, air mass characteristics and atmospheric circulation need further exploring with lengthy and spatially extensive datasets. Modelling efforts are also needed, with equilibrium and transient runs analysed for snow dynamics and additional runs geared specifically towards snow cover issues.

Snow cover research should examine the regional impacts of heat islands and land use on snow cover extent and duration. This information would be useful in the assessment of regional climate impacts, as well as establishing the stability of sites when it comes to analysing long-term records of snow.

Research is also needed to determine how variations in snow cover thickness and duration affect plant growth, food chains and wildlife migration.

#### 4.2 Permafrost

Most, if not all, of the research gaps in permafrost and permafrost processes can be filled through implementation of internationally conceived and managed programs of geocryological systematic observations designed to provide the necessary data. Such programs should involve the full spectrum of support of international programs and agencies (eg International Permafrost Association, WMO and IGBP) as well as national agencies. The required observation program should allow for the collection of the data necessary to calibrate permafrost/atmospheric temperature and energy flux models, indicate something of the scale of permafrost changes, both temporally and aerially, and allow climate change projections to be verified.

The required observation program should comprise three basic components with observations distributed throughout the major permafrost areas of the globe including continuous, discontinuous, marginal and marine permafrost zones, as well as alpine permafrost areas in both the northern and southern hemispheres:

- a number of first order sites (primary nodes) similar to the current sites in Canada, the Gydan, Yamal site of VSEGINGEO and the stations of the Permafrost Institute in the USSR;
- second order sites which would help generalise observations at the primary nodes; and
- remotely sensed data to provide a more comprehensive picture (although this data has the lowest level of accuracy and resolution, it does provide the broadest areal coverage).

The objective of this program should be to provide the data necessary to answer questions concerning basic permafrost processes and the depth, rate and extent of permafrost changes that can be expected as a result of projected climate change.

Early in the international collaboration, common protocols for systematic observational processes and equipment need to be established for all three components of this observation program to allow for intercomparison of observations. Procedural guidelines for analysis and establishing quality and reliability will also be needed. Data collected should be reasonably accessible.

The observation program at the 'primary node' sites should consist of year-round meteorological observations of air temperature, precipitation, snow cover and surface radiative, sensible, latent energy fluxes, widespread observations of ground temperature, active layer depth, soils, vegetation, hydrology and ground ice characteristics.

Within the context of global change and the permafrost regions, it will be necessary to maintain systematic observation at the sites for at least ten years (preferably 20 years), depending on the data taken and the scale of the changes observed.

Widespread observations at 'second order' sites are needed to generalise the observations taken at the 'primary node' sites. Integral to the observation programs at these sites are frost-tubes which can measure the greatest depth of active layer development and thus provide an indication of the amount of energy absorbed by the near surface over a season. Boreholes drilled to a depth of 60–100 m should also be included as part of the observation program at these sites. Data from these boreholes can provide information on the historical characteristics of any ice present, on how the ground temperatures have changed over the past century and determine the presence and distribution of ice (especially when coupled with ground probing radar surveys).

With respect to the third component of the observation program—remote sensing—the use of surface geophysical methods such as electromagnetic soundings and ground probing radar are beginning to provide knowledge of the local continuity of permafrost and ground-ice conditions. Several recent papers have demonstrated this capability (Rozenberg et al. 1985; LaFleche et al. 1987; and Todd et al. 1992). Repeated surveys with such equipment can provide early warning of changes in the subsurface, especially in the vicinity of structures (Judge et al 1991).

Both the primary and secondary component sites of the suggested observation program can also provide the ground-truthing for airborne and satellite-borne observations of landscape, snow, ground temperature, vegetation and shallow permafrost conditions.

Systematically observing the temperature, geometry and creep of permafrost at selected sites in alpine regions is a necessary component. Internationally coordinated systematic observation programs should be developed in various mountain areas of the world, especially with respect to borehole data and rock glacier photogrammetry.

National, regional and international integrated research programs should be directed at examining the processes and dynamic changes and interaction between the atmosphere, the biosphere and the cryosphere. This research should include modelling the heat and energy balance of permafrost; conducting integrated research on the impact of permafrost changes on terrestrial and coastal ecosystems (ie on the interrelations in the atmosphere - buffer zone - permafrost system); identifying processes causing changes in ground temperature profiles; and improving methodologies to observe changes systematically in permafrost extent and thickness, to determine ice content of permafrost (globally) and to determine the chemical characteristics of ground ice/permafrost areas.

Attempts to measure and model the heat and energy balance of mountain permafrost must accompany systematic observational activities in order to reach a better understanding and interpretation of the collected data. Sensitivity studies concerning the thermal and mechanical reaction of ice-rich permafrost on slopes in relation to reasonable scenarios of projected climate change will be possible in the near future. Such an approach requires systematic collection of the increasing amount of information on permafrost occurrence, and the design of computer-compatible algorithms for predicting permafrost distribution in mountain areas using digital terrain models in combinations with geographic information systems and—preferably infra-red—aerial photography. The same models would be able to show where anticipated warming trends could lead to rapid active layer thickening or even complete permafrost degradation. The corresponding information would form an important basis for directing attention towards especially sensitive areas and for improving systematic observation programs as a whole.

For impacts research studies, efforts should be directed towards systematic observations of structures (linear and buildings) within permafrost areas and the impacts of changes in the underlying permafrost on the stability of those structures. Research should be intensified on environmental factors and physical processes (eg soil temperature, thermal conductivity of soil layers, soil-moisture balance, active layer dynamics, thermokarst erosion) and their impacts on the accumulation and decomposition of peat, and the production of carbon dioxide and methane. This includes controlled experiments in the field as well as analysis of permafrost and peat cores.

In the case of permafrost, analyses indicate that changes in its characteristics are primarily determined by changes in climate and vegetative cover. The ability to separate the influences on permafrost temperature of changes in vegetative cover from those caused by changes in climate suggests that permafrost temperature can be a reliable indicator of climate change and can be used to reconstruct past climates. Collaboration among scientists working on climate change detection and those working on permafrost dynamics is essential to tapping this potential.

#### 4.3 Ice sheets

More statistical work is needed on the existing glacier data (two separate components of accumulation and ablation) to improve our knowledge of recent and projected climate changes, especially in the polar regions where data from other disciplines is especially sparse. Glacier-mass budget data must also be tied in with that derived from ice-core data to extend our knowledge of past climate change and place the present changes into true perspective (eg a recent study of ice cores from Wilkes Land, Antarctica, (Morgan et al. 1991) indicates increased snow accumulation since 1960, compatible with the mass input increase reported by Bentley and Giovinetto (1991)). The present warm period in the Canadian high Arctic is still considerably cooler than the climate there for over half the interglacial period beginning 10 000 years ago. The ice core record also shows that the short period immediately preceding the present warm one was the coldest for several thousand years. It appears that the present glacial recession is from major advances that took place during that cold period (Koerner and Fisher 1990). Seen in that context the present warming trend is not unusual.

Presently, the accurate measurement of the mass balance of Antarctica and Greenland is unattainable. The measurement of mass balance on small glaciers and ice sheets forms a powerful tool for detecting early signs of climate change of the nature projected by climate models as it represents an integration of the total energy flux over each glacier or ice cap. The two components of glacier balance—ie accumulation and ablation (ice or snow loss)—constitute measures of two separate parameters of the projected climate change (ie change in precipitation rate - substantially higher in the polar regions) and measurable higher ice/snow melt rates in summer. This is particularly important in polar glaciers as they are located in areas where the maximum climate change is projected to occur. To improve their effectiveness as indicators, it will be necessary to identify those changes resulting from local catchment characteristics and microclimate which can dominate climate change for many decades.

Changes of area and thickness on parts of dynamic glaciers are difficult to relate directly to climate change unless the response time of the glaciers is well known. Increasing thickness in the accumulation areas of southern Greenland (Zwally et al. 1989) contrast with decreasing thickness in the ablation zone below this (Lingle et al., in press). In the Canadian Arctic the accumulation areas of those ice sheets measured during the past 30 years show no evidence of changing elevation. Some glaciers, however, show a surface lowering in the ablation zone (Koerner 1989). Such measurements, when repeated, indicate whether precipitation and/or summer melting rates are changing. They complement mass balance observations.

It is still questionable, however, whether satellite measurements provide the desirable accuracy to detect surface elevation changes, particularly on small ice sheets where the required resolution could limit the usefulness of satellite-derived observations. Modern geodetic techniques or repeated precision-gravity measurements, coupled with GPS should be used to provide overlap with future satellite mapping using improved satellite sensors.

The gravity/GPS technique is presently being used on ice sheets in the Canadian Arctic and at seasonal Antarctic sites to detect elevation changes at the tops of ice sheet summits. Vertical (elevation) resolution also limits the use of satellite and GPS in areas where accumulation rates are low (ie  $< 20 \text{ g cm}^2 \text{y}^{-1}$ ) as changes in both the accumulation rate and elevation will be even lower.

To improve understanding of ice sheet and glacial changes and the impacts thereof, it is essential that existing long-term systematic observations programs be continued and that programs for representative glacier mass balance changes and associated climatic and hydrologic variables be expanded to provide a truly global network. This data should be supplemented with data derived from ice sheet elevation surveys by satellite (laser) altimetry such as that on the EOS/ERS series. Efforts should also be directed at improving systematic observations and assessments of iceberg calving from the Antarctic and Greenland ice sheets.

Enhanced integrated research programs at the national, regional and international levels should be directed towards examining the effects of glacier size fluctuations on the upper and lower drainage basin dynamics and continuing studies on the frequency and intensity of mass movements in relation to extreme meteorological events. Particular emphasis should be placed on promoting research in the slopes of high mountain regions aimed at better hazard (flooding, slope failure) appraisal.

The means of encouraging and, where necessary, facilitating the required support for these activities should be the subject of international dialogue. Specific requirements, recommendations, priorities and their implications

(globally and regionally) including considering both the needs and resource (human and monetary) requirements should be the subject of this dialogue.

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## **Appendix A. Analysis of current activity on regional impacts of climate change**

### **Steering Group:**

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# Appendix A. Analysis of current activity on regional impacts of climate change

## 1 Introduction

During the preparation of the First Assessment Report, it became clear that there were considerable gaps in our understanding of the potential impacts of climate change, particularly in the developing countries. As a result of the interest stimulated by the IPCC process and the activities of the World Climate Impact Studies Program, many country studies were initiated to remedy the deficiencies. The Asia-Pacific Seminar on climate change held in Nagoya in Japan on 23-26 January 1991 brought together a number of new studies in countries in the region and provided an extremely useful supplementary data source. Before proceeding with any further studies under the auspices of the IPCC, it was decided to survey the IPCC participating countries to assess the level of current activity and, in particular, identify regions where work was needed and issues which had not been identified in the six Tasks set by the IPCC Plenary. Accordingly, in June 1991, the Chairman of Working Group II circulated a questionnaire to all IPCC participating nations seeking their responses. Thirty-eight countries and eleven international organisations responded.

## 2 Methodology of assessment of responses

The responses were distributed through the IPCC Secretariat to members of the Steering Group set up at the Working Group II meeting in Geneva. Three members of the Steering Group, namely Dr Zwerva, Dr Tegart and Dr Nazarov, carried out analyses of the available responses. These analyses were discussed at a meeting in Amsterdam on 28 October 1991. Somewhat different approaches were used by the three groups in the presentation of the data. However, the conclusions reached were essentially similar with regard to the areas needing attention.

Attempts were made to increase the sample size by seeking further responses at the IPCC Plenary in November 1991. A few more countries responded following that meeting.

## 3 Results of the survey

Thirty-eight countries and eleven international NGOs responded to the survey. There was a particularly low level of response from Asian, North and Central American and South Pacific island countries. While there was a good response from developed countries, there were notable exceptions, including the United States and Germany.

The countries which responded were allocated to the six regions used by WMO (see Table 1) while the international organisations that responded are listed in Table 2.

## 4 Issues arising from the responses

### *Areas of activity*

The most extensive amount of work has been undertaken in OECD countries, where impacts research has been undertaken across all sectors listed in the questionnaire. In developing regions the amount of research activity varies widely. In the eleven African countries which responded, although there had often been extensive consultation, only two countries were undertaking any activity at all (these being Senegal and Cote D'Ivoire which are undertaking a wide range of work on impacts). This and the lack of overall response would indicate that little substantial work has been done in this region on impacts.

In contrast, research activity in some South American and Asian countries, notably Chile, China, Saudi Arabia, Vietnam and Venezuela cover quite a range of sectors. However, the other countries which responded had a smaller range of activity, and given the low level of response from these regions, it is not possible to extrapolate from such a small sample.

Several of the international NGOs which replied, particularly United Nations bodies, are carrying out impacts research in a range of sectors. It would appear that much of this work is being undertaken in developing countries.

Several countries have also undertaken work in a number of areas of activity outside the IPCC Working Group II sectors, including impacts on:

- social issues
- tourism
- UV-B radiation
- economic issues
- recreation
- population
- desertification.

### *Priority areas*

Of the sectors listed in the questionnaire, sectors a, b, c, d and e were all identified as priority areas for future action. Areas a, c and d were the sectors most often

emphasised in the developing countries. A few island countries also identified cyclones and extreme climate events. Sectors outside the ones identified by the IPCC include:

- economic issues
- cyclones and other extreme events
- desertification
- recreation and tourism.

#### *Areas for future attention by IPCC*

All regions suggested sectoral areas, other than those listed in the questionnaire, which require further attention by the IPCC. In particular, African and Asian countries suggested more activity on desertification. The suggested areas are:

- desertification
- global security
- UV-B radiation
- cyclones and other extreme events
- the ionosphere
- recreation and tourism
- fishing
- aquatic ecosystems
- migration
- social and economic issues
- mountain regions
- biological adaptations.

#### *Assistance required*

Only developing countries identified a need for assistance, generally in the form of grants, expert advice, training and international seminars. Two developed countries indicated that grants could be utilised.

*Table 1: Countries which responded (by WMO region)*

<p>I Africa</p> <ul style="list-style-type: none"> <li>Cote d'Ivoire</li> <li>Gambia</li> <li>Guinea</li> <li>Malawi</li> <li>Mauritius</li> <li>Rwanda</li> <li>Senegal</li> <li>Seychelles</li> <li>Tunisia</li> <li>Uganda</li> <li>Zimbabwe</li> </ul>	<p>II Asia</p> <ul style="list-style-type: none"> <li>China</li> <li>Japan</li> <li>Pakistan</li> <li>Saudi Arabia</li> <li>Vietnam</li> </ul>
<p>III South America</p> <ul style="list-style-type: none"> <li>Argentina</li> <li>Bolivia*</li> <li>Chile*</li> <li>Paraguay*</li> <li>Uruguay*</li> <li>Venezuela*</li> </ul>	<p>IV North and Central America</p> <ul style="list-style-type: none"> <li>Bahamas</li> <li>Canada</li> <li>Cuba</li> </ul>
<p>*information on impact studies only</p>	
<p>V South-West Pacific</p> <ul style="list-style-type: none"> <li>Australia</li> <li>New Zealand</li> <li>Papua New Guinea</li> <li>Philippines</li> </ul>	<p>VI Europe</p> <ul style="list-style-type: none"> <li>Denmark</li> <li>Finland</li> <li>France</li> <li>Ireland</li> <li>The Netherlands</li> <li>Norway</li> <li>Poland</li> <li>Switzerland</li> <li>United Kingdom</li> <li>Russia</li> </ul>

Table 2: *International organisations which responded*

FAO	Food and Agriculture Organisation
FOE	Friends of the Earth (UK)
GEMS	Global Environment Monitoring System (UNEP)
ICSU	International Council of Scientific Unions
IHP	International Hydrological Program (UNESCO)
IIASA	International Institute for Applied Sys- tems Analysis
ILO	International Labour office
IOC	Intergovernmental Oceanographic Commission
OECD	Organisation for Economic Co-operation and Development
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WCI	World Coal Institute

**Activity areas and degree of consultation**

## Activity areas

- a) Agriculture and forestry
- b) Natural terrestrial ecosystems
- c) Hydrology and water resources
- d) Energy, industry, transportation, human settle-  
ments, health and air quality
- e) World's oceans and coastal zones
- f) Cryosphere including the special problems of  
permafrost

## I Africa

<i>Country</i>	<i>Consultation</i>	<i>Activity areas</i>
Cote D'Ivoire	extensive	a, b, c, d
Gambia	extensive	none
Guinea	limited	none
Malawi	limited	none
Mauritius	extensive	available in future
Rwanda	extensive	none
Senegal	limited	a, b, c, d, e
Seychelles	none	none
Tunisia	not given	not given
Uganda	extensive	none
Zimbabwe	not given	none

## II Asia

China	extensive	a, b, c, d, e, f
Japan	limited	a, b, c, d, e, f social & economic impacts
Indonesia	-	e
Pakistan	limited	no specific areas, general study only
Saudi Arabia	limited	c, d, e desertification
Vietnam	limited	a, b, c, d, e

## III South America

Argentina	limited	a, b, c, d
Bolivia	-	none
Chile	-	a, b, b, d, e
Paraguay	-	unsure
Uruguay	-	unsure
Venezuela	extensive	a, b, c, d, e

## IV North and Central America

Bahamas	not given	none
Canada	extensive	a, b, c, d, e, f socioeconomic impacts recreation, population
Cuba	limited	a, b, c, d (human settle), e

## V South-West Pacific

Australia	extensive	a, b, c, d, e, f UV-B radiation
New Zealand	limited	a, b, c, e, f
Papua New Guinea		d, e
Philippines	limited	a, c

## VI Europe

Denmark	limited	a, b, c, d, e tourism economy
Finland	extensive	a, b, c, d, e, f
France	extensive	a, b, c
Ireland	limited	a, b, c, d, e
The Netherlands	limited	a, b, c, d, e, f
Norway	extensive	a, b, c, d, e, f
Poland	extensive	a, b, c, e
Switzerland	extensive	a, b, c, d, e, f
United Kingdom	extensive	a, b, c, d, e, f
Russia	extensive	a, b, c, d, e

*Highest priority areas*

<i>Country</i>	<i>Priority areas</i>
<b>I Africa</b>	
Cote D'Ivoire	a, b, c
Gambia	a, b, c, d (human settlements & health); e (Coastal zones)
Guinea	a, b, c
Malawi	estimates of regional ecological and socioeconomic impacts and baseline conditions; case studies of the above; preparation of a synthesis report
Mauritius	c sea-level rise & impacts on coastal zone; agriculture, sugarcane; increased cyclone impact on coastal areas
Rwanda	a, c, d
Senegal	a, c, d
Seychelles	coastal erosion; impact on ocean environment within EEZ; extreme events, eg tropical cyclones and storm surges
Tunisia	a, c ecosystems affected by desertification
Uganda	a, c, d
Zimbabwe	a, c, d tourism & recreation
<b>II Asia</b>	
China	a, c, d
Japan	no priorities set
Pakistan	a, c, d
Saudi Arabia	c desertification; sea-level rise; increased frequency of extreme weather events
Vietnam	a, b, c, e
<b>III South America</b>	
Argentina	a, c, d
Venezuela	a, c energy, industry, transportation, air quality, precipitation patterns
<i>Country</i>	<i>Priority areas</i>
<b>IV North and Central America</b>	
Bahamas	none given
Canada	a, b, c, f
Cuba	a, c, e

## V South-West Pacific

Australia	a, c natural ecosystems (including marine); energy and industry
New Zealand	coastal, agricultural, indigenous ecosystems
Papua New Guinea	e impact of extreme events such as cyclones
Philippines	a, d energy, industry, human settlements

## VI Europe

Denmark	a, b, c, d, e tourism economy
Finland	boreal forest/ forestry/ peatlands hydrology/ freshwater ecosystems/ water resources Baltic Sea
France	Forests, soils and grasslands
Ireland	a, b, c, d, e
The Netherlands	coastal zone management socioeconomic consequences & long-term sustainable development ecosystems
Norway	How fast ecosystems can change before irreversible damage; Gulf Stream; effect of climate change on other environmental monitoring programs; economic consequences of climate change;
Poland	a, b, c
Switzerland	energy supply; mountain areas; agriculture;
United Kingdom	critical sensitivities (soil, water, flora, fauna); hydrology; coastal and estuarine zones
Russia	agriculture and forestry; hydrology and water resources; energy, industry and transportation; cryosphere

*Areas for future IPCC attention*

## I Africa

Rwanda	desertification
Senegal	drought and desertification
Seychelles	fisheries; tourism
Tunisia	desertification

## II Asia

China	desertification; extreme events
Saudi Arabia	desertification

## III South America

Argentina	interrelations between upper and middle atmosphere (ionosphere)
Venezuela	aquatic ecosystems

## IV North and Central America

Canada	global security
Cuba	tourism

## V South-West Pacific

Australia	fisheries — marine and inland; recreation and tourism; migration; aquaculture; social structure; economy; integrated socioeconomic issues
New Zealand	pastures
Papua New Guinea	impact of extreme events such as cyclones

## VI Europe

The Netherlands	impact of UV-B radiation on health; crops and ecosystems; socioeconomic impacts
Norway	Economic consequences
Switzerland	Mountain regions; human perception of climate change problems; risk analysis
United Kingdom	Biological adaptations

*Assistance required*

## I Africa

Cote d'Ivoire	subsidise research and training at specialised centres; assist with information and publicity
Gambia	national seminar series; consultancy mission to identify needs; grants, expertise and training;
Guinea	technical and financial assistance in cooperation of an industrialised country external training; provision of experts

Malawi	provision of experts; training schemes at overseas centres
Mauritius	grants, expert advice, seminars
Rwanda	provision of grants and experts training at overseas centres
Senegal	equipment for surveillance systems international association of national experts; provision of experts for short periods in case of emergency;
Seychelles	IPCC information exchange seminars; vulnerability to SLR case study for the Seychelles; grants or equipment for data acquisition
Tunisia	grants; training within the country or at centres overseas
Uganda	grants, expert advice, training
Zimbabwe	none

## II Asia

China	none
Pakistan	grants
Saudi Arabia	training, provision of experts
Vietnam	none

## III South America

Argentina	assistance will be required but not specified - IV WGII session will analyse this matter
Venezuela	grants

## IV North and Central America

Bahamas	provision of equipment from EEC
Cuba	provision of computers and software and training; provision of methodology for impact assessment

## V South-West Pacific

Australia	although no assistance specifically required there is further research that could be undertaken if additional funds were available
Papua New Guinea	provision of experts
Philippines	training, participation in international fora

## VI Europe

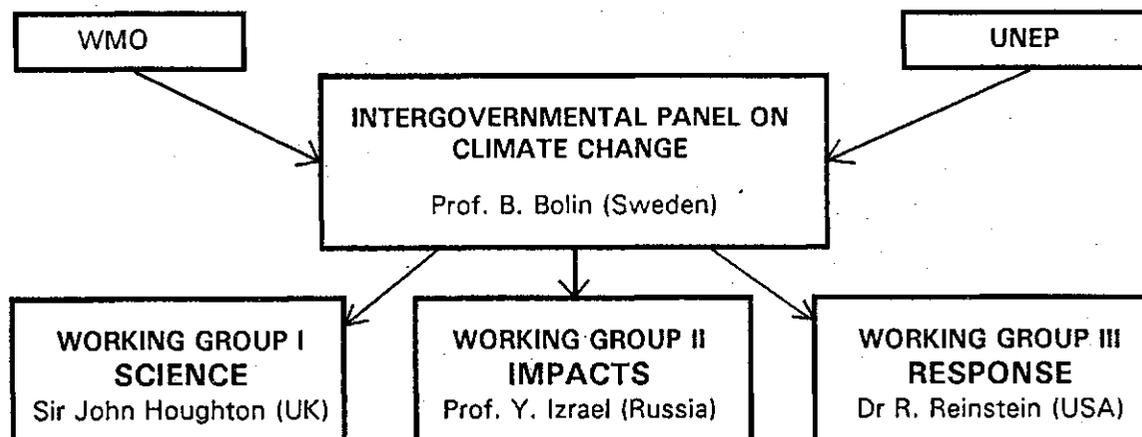
France	possibly grants
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All other participating countries gave a nil response.

*Responses from international non-government organisations*

<i>Organisation</i>	<i>Activity areas</i>	<i>Priority areas</i>
Int'l Institute for Applied Systems Analysis	a, b, c, d	
International Labour Office	d — employment	
Friends of the Earth (UK)		a — water resources b — biological diversity e — sea-level rise
World Coal Institute		- investigating historical data - quantifying impacts at pressure points
Global Environment Monitoring System (UNEP)	methodology for climate impact assessment, especially re a and d	
OECD	socioeconomic impacts	- physical and economic impacts over a longer time horizon - connecting physical impacts with economic and social impacts
International Oceanographic Commission	work re e and f, with linkages to b,c and d	
International Council of Scientific Unions	IGBP Project re b Proposed project re e	
Food and Agricultural Organisation	a, c, e	
UNESCO		
- International Hydrological Programme	c	
- Working Group on Mean Sea-Level Rise and its influence on the Coastal Zone	e	

## Appendix B. Organisation of IPCC and Working Group II



### IPCC

Chairman: Professor B Bolin (Sweden)  
Vice Chairman: Dr A Algain (Saudi Arabia)  
Rapporteur: Dr J A Adejokun (Nigeria)  
Secretary: Dr N Sundararaman (WMO)

### Working Group II

Chairman: Professor Yu A Izrael (Russia)  
Vice Chairmen: Professor O Canziani (Argentina)  
Dr S Nishioka (Japan)  
Professor R S Odingo (Kenya)  
Dr W J McG Tegart (Australia)



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## Glossary of acronyms

AAC	Atmospheric Action Centres
ACSYS	Arctic Climate System Study
AMAP	Arctic Monitoring and Assessment Programme
BCC	Basal Cell Carcinoma
BRE	Building Research Establishment (Watford, UK)
CERN	Chinese Ecological Research Network
CSM	Climate System Monitoring (Project)
ECN	Environmental Change Network (UK)
ENSO	El Niño/Southern Oscillation
FAO	Food and Agriculture Organisation
FOE	Friends of the Earth
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEMS	Global Environmental Monitoring System
GHG	Greenhouse Gas(es)
GIS	Global Information System
GISS	Goddard Institute of Space Studies
GOOS	Global Ocean Observing System
IBP	International Biological Programme
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IGOSS	Integrated Global Ocean Services System
IHP	International Hydrological Program
IJAASA	International Institute for Applied Systems Analysis
ILO	International Labour Office
INC	Intergovernmental Negotiating Committee
IOC	Intergovernmental Oceanographic Commission
IOC	International Ozone Commission
IPCC	Intergovernmental Panel on Climate Change
LICC	Landscape-ecological Impact of Climate Change
MAB	Man and the Biosphere
MINK	Missouri-Iowa-Nebraska-Kansas
OECD	Organization for Economic Cooperation and Development
SAT	Surface Air Temperature
SCC	Squamous Cell Carcinoma
TEMA	Terrestrial Ecosystem Monitoring and Assessment
UNCED	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
US DOE	United States Department of the Environment
US EPA	United States Environmental Protection Authority
US NSF	United States
WCDP	World Climate Data Programme
WCI	World Coal Institute
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

**This report is a Supplement to the 1990 Report of the Impacts Assessment Working Group of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was set up jointly by the World Meteorological Organisation and the United Nations Environment Program in 1988 to provide an authoritative international consensus of scientific opinion on global warming. This Supplement reviews the key conclusions of the 1990 Report in the light of new evidence focussing on eight main areas:**

- Agriculture and Forestry
- Water and Hydrology
- Natural Terrestrial Ecosystems
- Terrestrial Component of the Cryosphere
- Energy, Human Settlement, Transport and Industrial Sectors, Human Health, Air Quality and Changes in UV-B Radiation
- World Oceans and Coastal Zones
- Preliminary Guidelines for Assessing Impacts of Climate Change
- Systematic Observations to Identify Climate Change Consequences.

Scientists throughout the world participated in the preparation and review of this assessment, thus continuing the approach which gained such widespread acceptance and authority for the 1990 IPCC Report. It represents the continuing effort of the international scientific community to communicate to policymakers, at both national and international levels, the very latest scientific knowledge and understanding of the complex issues surrounding climate and climate change.

The original report, *Climate Change The IPCC Impacts Assessment* is available from the Australian Government Publishing Service.

