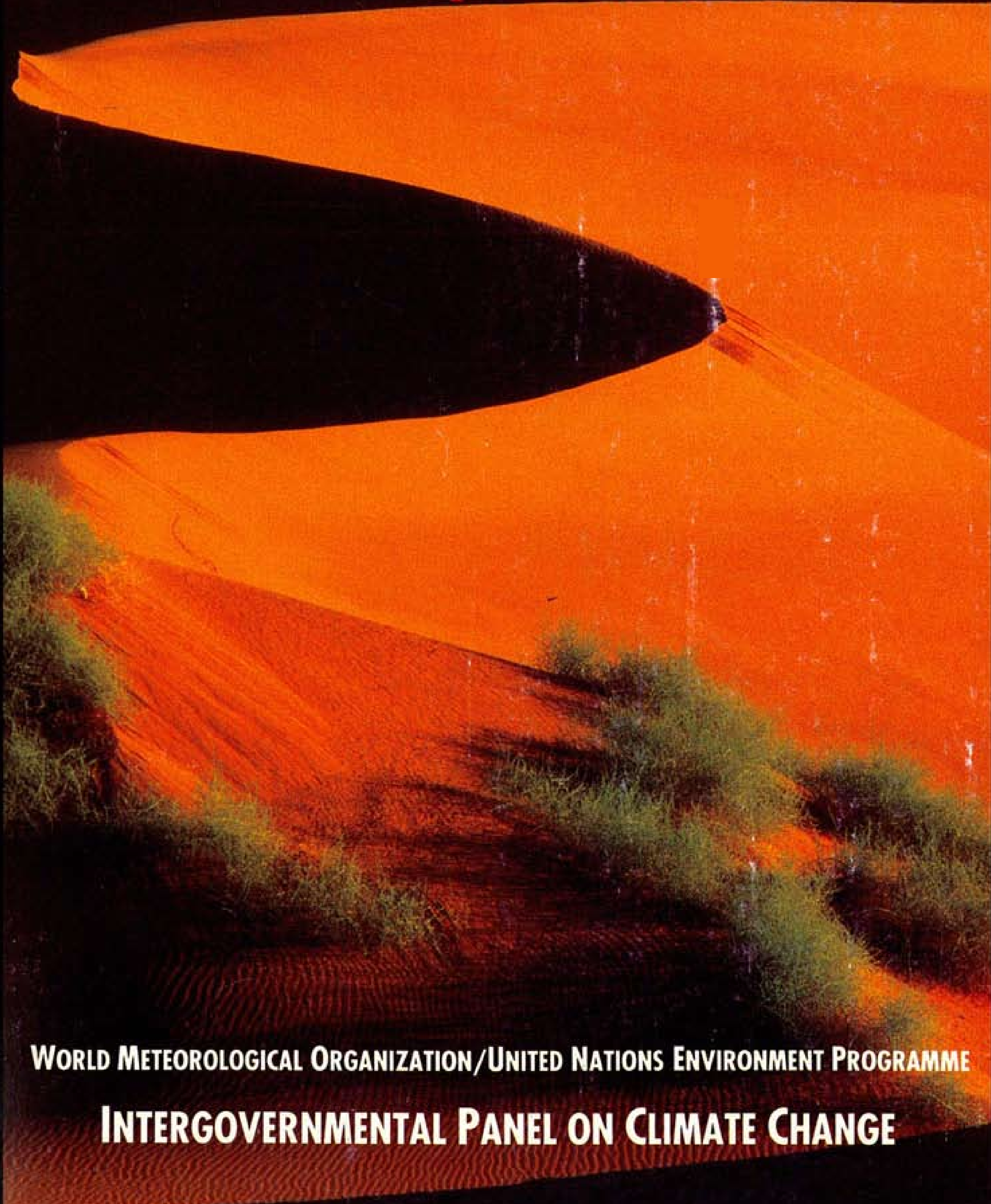
CLIMATE CHANGE

The IPCC Impacts Assessment



WORLD METEOROLOGICAL ORGANIZATION/UNITED NATIONS ENVIRONMENT PROGRAMME

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

This is the final Report of Working Group II of the Intergovernmental Panel on Climate Change, which is sponsored jointly by the World Meteorological Organization and the United Nations Environment Programme. The report considers the potential impacts of climate change. Several hundred working scientists from many countries have participated in the preparation and review of the scientific data. The result is a unique statement on impacts of climate change with a breadth not previously achieved by the international scientific community. The impact assessments cover: agriculture and forestry, natural terrestrial ecosystems, hydrology and water resources, human settlement and socio-economic activities, oceans and coastal zones and the cryosphere. The information presented here is the best available at present. It will inform the necessary scientific, political and economic debates and negotiations that can be expected in the immediate future. Appropriate strategies in response to the issue of climate change can be based on the scientific foundation that the Report provides. The Report is, therefore, an essential reference for all who are concerned with climate change and its consequences.

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Edited by

W.J. McG. Tegart, G.W. Sheldon and D.C. Griffiths

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Report prepared for IPCC by Working Group II

Edited by

W.J. McG. Tegart, G.W. Sheldon and D.C. Griffiths

WMO **UNEP**

Acknowledgments

This report is a unique example of international cooperation over a wide range of disciplines in a relatively short time frame. While literally hundreds of scientists in a large number of countries have contributed information and peer-reviewed the material, the major task has fallen on the principal authors of the various chapters. The authors are identified at the start of each chapter.

The compilation and editing of the overall report has been carried out by Mr C. Griffiths, Mr G.W. Sheldon and Dr WJ.McG. Tegart from Australia.

We believe that the process of working together to gain a better understanding of the potential of global climate change on regions and nations has been important in building a basis for continuing international cooperation and we wish to offer our sincere thanks to all who have participated.

Professor Yu. A. Izrael (USSR) Chairman
Dr M. Hashimoto (Japan) Co-Vice-Chairman
Dr WJ.McG. Tegart (Australia) Co-Vice-Chairman

Foreword

In making its Impacts Assessment, Working Group II has built on the available country assessments, taking into account significant work undertaken more recently. By its very nature, such work is distributed over many fields. There are many uncertainties in them, and some results have yet to be published. While some countries have produced assessments of the impact of climate change on their economic, industrial and social structure, there has not been a comprehensive assessment on a global scale.

In the preparation of the Assessment, many of the active scientists working in the industrialised countries have been involved. Because of lack of sufficient funding, the contribution from the developing countries has been less than hoped for, and it is clear that much further work needs to be carried out to develop a better framework for economic decisions in a number of countries, notably in Africa and South America. Over 200 contributors are identified in the report, but they have been supported by many others. Because of the diversity of the topics, it has been difficult to carry out a full peer review of the whole report. Chapters have been reviewed by selected organisations, both national and international, and five meetings of lead authors and major contributors, over a period of one and a half years, have helped to shape the final report. An extensive technical review was carried out by the US National Climate Program in early 1990 and helped to ensure a high degree of consensus among authors and reviewers regarding the results presented. Joint Soviet American research in the area of climate change provided a significant input. Thus the Assessment is an authoritative statement of the views of the majority of the international scientific community at this time.

The accompanying Policymakers' Summary, based closely on the conclusions of the Assessment, has been prepared particularly to meet the needs of those without a strong background in science who need a clear statement of the present status of scientific knowledge and the associated uncertainties. It is clear from the report that comprehensive estimates of the physical and biological effects of climate change at the regional level are difficult. Confidence in regional estimates of critical climate factors is low, particularly of precipitation and soil moisture. Much more research is needed to refine the estimates of potential impacts and I urge Governments to continue and increase their support of research on climate change.

It gives me pleasure to acknowledge the contributions of so many, in particular the lead authors, who have given freely of their expertise and time in the preparation of this report. I also acknowledge the contribution of the core team at the State Committee for Hydrometeorology who were responsible for organising meetings in the USSR. Particular acknowledgement is due to Dr Greg Tegart, my Co-Vice Chairman from Australia, who together with Mr Colin Griffiths and Mr Gordon Sheldon were responsible for the compilation and editing of the overall report in Australia. Thanks are also due to Dr M Hashimoto, my other Co-Vice-Chairman from Japan.

I am confident that the assessment and its summary will provide a sound basis for the forthcoming discussions and negotiations on the appropriate strategy and action regarding the issue of climate change which is potentially the greatest global environmental challenge facing humankind.

Prof Yu A Izrael
Chairman, IPCC Working Group II
Chairman, USSR State Committee for Hydrometeorology
Moscow
October 1990

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Preface

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by us in 1988. Professor Bert Bolin is the Chairman of the Panel. The Panel's charge was to:

a. assess the scientific information that is related to the various components of the climate change issue, such as emissions of major greenhouse gases and modification of the Earth's radiation balance resulting therefrom, and that needed to enable the environmental and socio-economic consequences of climate change to be evaluated; and

b. formulate realistic response strategies for the management of the climate change issue.

The Panel began its task by establishing its Working Groups I, II and III respectively to:

a. assess available scientific information on climate change;

b. assess environmental and socio-economic impacts of climate change; and

c. formulate response strategies.

The panel also established a Special Committee on the Participation of Developing Countries to promote, as quickly as possible, the full participation of developing countries in its activities.

The Panel has completed its First Assessment Report (FAR). The FAR consists of

* the overview

* the policymakers summaries of the IPCC Working Groups and Special Committee on the participation of Developing Countries

* the reports of the IPCC Working Groups

The Overview and the policymakers summaries are to be found in a single volume. The reports of the Working Groups are being published individually.

The present volume is based upon the findings of Working Group II. It should be read in the context of the full IPCC first assessment report.

The Chairman of Working Group II, Professor Yuri Izrael, and his Secretariat, have succeeded in mobilising the co-operation and enthusiasm of hundreds of scientists from all over the world. They have produced a volume of unique breadth, and a Policymakers Summary which translates these complex scientific issues into language understandable to the non-specialist.

We take this opportunity to congratulate and thank the Chairman and his Co-Vice-Chairmen, Dr W J McG Tegart and Dr M Hashimoto, for a job well done.

G O P Obasi
Secretary-General
World Meteorological Organization

M K Tolba
Executive Director
United Nations Environment Programme

Policymakers' summary

The IPCC Working Groups on scientific analysis (Working Group I), impacts (Working Group II) and response strategies (Working Group III) were established in November 1988 and proceeded to work in parallel under instructions from IPCC. The responsibility of Working Group II is to describe the environmental and socioeconomic implications of possible climate changes over the next decades caused by increasing concentrations of greenhouse gases.

The report of Working Group II is based on the work of a number of subgroups, using independent studies which have used different methodologies. Based on the existing literature, the studies have used several scenarios to assess the potential impacts of climate change. These have the features of:

(i) an effective doubling of CO_2 in the atmosphere between now and 2025 to 2050 for a 'business-as-usual' scenario;

(ii) a consequent increase of global mean temperature in the range of 1.5°C to 4°-5°C;

(iii) an unequal global distribution of this temperature increase, namely a smaller increase of half the global mean in the tropical regions and a larger increase of twice the global mean in the polar regions; and

(iv) a sea-level rise of about 0.3-0.5 m by 2050 and about 1 m by 2100, together with a rise in the temperature of the surface ocean layer of between 0.2° and 2.5°C.

These scenarios pre-date, but are in line with, the recent assessment of Working Group I which, for a 'business-as-usual' scenario (scenario A in Working Group I Report) has estimated the magnitude of sea-level rise at about 20 cm by 2030 and about 65 cm by the end of the next century. Working Group I has also predicted the increase in global mean temperatures to be about 1°C above the present value by 2025 and 3°C before the end of the next century.

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 Nino can cause significant impacts on agriculture and human settlement. The predicted population explosion 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 most severely in regions already under stress, mainly the developing countries. Human-induced climate change due to continued uncontrolled emissions will accentuate these impacts. For instance, climate change, pollution and ultraviolet-B radiation from ozone depletion can interact, reinforcing their damaging effects on materials and organisms. Increases in atmospheric concentrations of greenhouse gases may lead to irreversible change in the climate which could be detectable by the end of this century.

Comprehensive estimates of the physical and biological effects of climate change at the regional level are difficult. Confidence in regional estimates of critical climatic factors is low. This is particularly true of precipitation and soil moisture, where there is considerable disagreement between various general circulation model and palaeoanalog results. Moreover, there are several scientific uncertainties regarding the relationship between climate change and biological effects and between these effects and socioeconomic consequences.

This report does not attempt to anticipate any adaptation, technological innovation or any other measures to diminish the adverse effects of climate change that will take place in the same time frame. This is especially important for heavily managed sectors, eg agriculture, forestry and public health. This is one of the responsibilities of Working Group III.

Finally, the issue of timing and rates of change need to be considered; there will be lags between:

i) emissions of greenhouse gases and doubling of concentrations;

ii) doubling of greenhouse gas concentrations and changes in climate;

iii) changes in climate and resultant physical and biological effects; and

iv) changes in physical and ecological effects and resultant socioeconomic (including ecological) consequences. The shorter the lags, the less the ability to cope and the greater the socioeconomic impacts.

There is uncertainty related to these time lags. The changes will not be steady and surprises cannot be ruled out. The severity of the impacts will depend to a large degree on the rate of climate change.

Despite these uncertainties, Working Group II has been able to reach some major conclusions, which are:

Agriculture and forestry

Sufficient evidence is now available from a variety of different studies to indicate that changes of climate would have an important effect on agriculture and livestock. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease. Negative impacts could be felt at the regional level as a result of changes in weather and pests associated with climate change, and changes in ground-level ozone associated with pollutants, necessitating innovations in technology and agricultural management practices. There may be severe effects in some regions, particularly decline in production in regions of high present-day vulnerability that are least able to adjust. These include Brazil, Peru, the Sahel Region of Africa, Southeast Asia, the Asian region of the USSR and China. There is a possibility that potential productivity of high and mid latitudes may increase because of a prolonged growing season, but it is not likely to open up large new areas for production and it will be mainly confined to the Northern Hemisphere.

Patterns of agricultural trade could be altered by decreased cereal production in some of the currently high-production areas, such as Western Europe, southern US, parts of South America and western Australia. Horticultural production in mid-latitude regions may be reduced. On the other hand, cereal production could increase in northern Europe. Policy responses directed to breeding new plant cultivars, and agricultural management designed to cope with changed climate conditions, could lessen the severity of regional impacts. On balance, the evidence suggests that in the face of estimated changes of climate, food production at the global level can be maintained at essentially the same level as would have occurred without climate change; however, the cost of achieving this is unclear. Nonetheless, climate change may intensify difficulties in coping with rapid population growth. An increase or change in UV-B radiation at ground level resulting from the depletion of stratospheric ozone will have a negative impact on crops and livestock.

The rotation period of forests is long and current forests will mature and decline during a climate in which they are increasingly more poorly adapted. Actual impacts depend on the physiological adaptability of trees and the host-parasite relationship. Large losses from both factors in the form of forest declines can occur. Losses from wild-fire will be increasingly extensive. The climate zones which control species distribution will move poleward and to higher elevations. Managed forests require large inputs in terms of choice of seedlot and spacing, thinning and protection. They provide a variety of products from fuel to food. The degree of dependency on products varies among countries, as does the ability to cope with and to withstand loss. The most sensitive areas will be where species are close to their biological limits in terms of temperature and moisture. This is likely to be, for example, in semi-arid areas. Social stresses can be expected to increase and consequent anthropogenic damage to forests may occur. These increased and non-sustainable uses will place more pressure on forest investments, forest conservation and sound forest management.

Natural terrestrial ecosystems

Natural terrestrial ecosystems could face significant consequences as a result of the global increases in the atmospheric concentrations of greenhouse gases and the associated climatic changes. Projected changes in temperature and precipitation suggest that climatic zones could shift several hundred kilometres towards the poles over the next fifty years. Flora and fauna would lag behind these climatic shifts, surviving in their present location and, therefore, could find themselves in a different climatic regime. These regimes may be more or less hospitable and, therefore, could increase productivity for some species and decrease that of others. Ecosystems are not expected to move as a single unit, but would have a new structure as a consequence of alterations in distribution and abundance of species.

The rate of projected climate changes is the major factor determining the type and degree of climatic impacts on natural terrestrial ecosystems. These rates are likely to be faster than the ability of some species to respond and responses may be sudden or gradual.

Some species could be lost owing to increased stress leading to a reduction in global biological diversity. Increased incidence of disturbances such as pest outbreaks and fire are likely to occur in some areas and these could enhance projected ecosystem changes.

Consequences of CO_2 enrichment and climate change for natural terrestrial ecosystems could be modified by other environmental factors, both natural and man-induced (eg by air pollution).

Most at risk are those communities in which the options for adaptability are limited (eg montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves) and those communities where climatic changes add to existing stresses.

The socioeconomic 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 welfare. Changes in the availability of food, fuel, medicine, construction materials and income are possible as these ecosystems are changed. Important fibre products could also be affected in some regions.

Hydrology and water resources

Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions and those humid areas where demand or pollution has led to water scarcity. Little is known about regional details of greenhouse gas-induced hydrometeorological change. It appears that many areas will have increased precipitation, soil moisture and water storage, thus altering patterns of agricultural, ecosystem and other water use. Water availability will decrease in other areas, a most important factor for already marginal situations, such as the Sahelian zone in Africa. This has significant implications for agriculture, for water storage and distribution, and for generation of hydroelectric power. In some limited areas, for example, under the assumed scenario of a 1°C to 2°C temperature increase, coupled with a 10% reduction in precipitation, a 40-70% reduction in annual runoff could occur. Regions such as Southeast Asia, that are dependent on unregulated river systems, are particularly vulnerable to hydrometeorological change. On the other hand, regions such as the western USSR and western United States that have large regulated water resource systems are less sensitive to the range of hydrometeorological changes in the assumed greenhouse scenario.

In addition to changes in water supply, water demand may also change through human efforts to conserve, and through improved growth efficiency of plants in a higher CO_2 environment. Net socioeconomic consequences must consider both supply and demand for water. Future design in water resource engineering will need to take possible impacts into account when considering structures with a life span to the end of the next century. Where precipitation increases, water management practices, such as urban storm drainage systems, may require upgrading in capacity. Change in drought risk represents potentially the most serious impact of climate change on agriculture at both regional and global levels.

Human settlements: the energy, transport, and industrial sectors; human health; air quality and changes in ultraviolet-B radiation

The most vulnerable human settlements are those especially exposed to natural hazards, eg coastal or river flooding, severe drought, landslides, severe wind storms and tropical cyclones. The most vulnerable populations are in developing countries, in the lower income groups, residents of coastal lowlands and islands, populations in semi-arid grasslands, and the urban poor in squatter settlements, slums and shanty towns, especially in megacities. In coastal lowlands such as in Bangladesh, China and Egypt, as well as in small island nations, inundation due to sea-level rise and storm surges could lead to significant movements of people. Major health impacts are possible, especially in large urban areas, owing to changes in availability of water and food and increased health problems due to heat stress spreading of infections. Changes in precipitation and temperature could radically alter the patterns of vector-borne and viral diseases by shifting them to higher latitudes, thus putting large populations at risk. As similar events have in the past, these changes could initiate large migrations of people, leading over a number of years to severe disruptions of settlement patterns and social instability in some areas.

Global warming can be expected to affect the availability of water resources and biomass, both major sources of energy in many developing countries. These effects are likely to differ between and within regions with some areas losing and others gaining water and biomass. Such changes in areas which lose water may jeopardise energy supply and materials essential for human habitation and energy. Moreover, climate change itself is also likely to have different effects between regions on the availability of other forms of renewable energy such as wind and solar power. In developed countries some of the greatest impacts on the energy, transport and industrial sectors may be determined by policy responses to climate change such as fuel regulations, emission fees or policies promoting greater use of mass transit. In developing countries, climate-related changes in the availability and price of production resources such as energy, water, food and fibre may affect the competitive position of many industries.

Global warming and increased ultraviolet radiation resulting from depletion of stratosphere ozone may produce adverse impacts on air quality such as increases in ground-level ozone in some polluted urban areas. An increase of UV-B radiation intensity at the earth's surface would increase the risk of damage to the eye and skin and may disrupt the marine food chain.

Oceans and coastal zones

Global warming will accelerate sea-level rise, modify ocean circulation and change marine ecosystems, with considerable socioeconomic consequences. These effects will be added to present trends of rising sea-level, and other effects that have already stressed coastal resources, such as pollution and overharvesting. A 30-50 cm sea-level rise (projected by 2050) will threaten low islands and coastal zones. A i m rise by 2100 would render some island countries uninhabitable, displace tens of millions of people, seriously threaten low-lying urban areas, flood productive land, contaminate fresh water supplies and change coastlines. All of these impacts would be exacerbated if droughts and storms become more severe. Coastal protection would involve very significant costs. Rapid sea-level rise would change coastal ecology and threaten many important fisheries. Reductions in sea ice will benefit shipping, but seriously impact on ice-dependent marine mammals and birds.

Impacts on the global oceans will include changes in the heat balance, shifts in ocean circulation which will affect the capacity of the ocean to absorb heat and CO_2, and changes in upwelling zones associated with fisheries. Effects will vary by geographic zones, with changes in habitats, a decrease in biological diversity and shifts in marine organisms and productive zones, including commercially important species. Such regional shifts in fisheries will have major socioeconomic impacts.

Seasonal snow cover, ice and permafrost

The global areal extent and volume of elements of the terrestrial cryosphere (seasonal snow cover, near-surface layers of permafrost and some masses of ice) will be substantially reduced. These reductions, when reflected regionally, could have significant impacts on related ecosystems and social and economic activities. Compounding these impacts in some regions is that, as a result of the associated climatic warming positive feedbacks, the reductions could be sudden rather than gradual.

The areal coverage of seasonal snow and its duration are projected to decrease in most regions, particularly at mid-latitudes, with some regions at high latitudes possibly experiencing increases in seasonal snow cover. Changes in the volume of snow cover, or the length of the snow cover season, will have both positive and negative impacts on regional water resources (as a result of changes in the volume and the timing of runoff from snowmelt); on regional transportation (road, marine, air and rail); and on recreation sectors.

Globally, the ice contained in glaciers and ice sheets is projected to decrease, with regional responses complicated by the effect of increased snowfall in some areas which could lead to accumulation of ice. Glacial recession will have significant implications for local and regional water resources, and thus impact on water availability and on hydroelectric power potential. Glacial recession and loss of ice from ice sheets will also contribute to sea-level rise.

Permafrost, which currently underlies 20-25% of the land mass of the Northern Hemisphere, could experience significant degradation within the next 40-50 years. Projected increases in the thickness of the freeze-thaw (active) layer above the permafrost and a 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. As a result, overlying ecosystems could be significantly altered and the integrity of man-made structures and facilities reduced, thereby influencing existing human settlements and development opportunities.

Future action

The results of the Working Group II studies highlight our lack of knowledge, particularly at the regional level and in areas most vulnerable to climate change. Further national and international research is needed on:

- regional effects of climate change on crop yields, livestock productivity and production costs;

- identification of agricultural management practices and technology appropriate for changed climate;

- factors influencing distribution of species and their sensitivity to climate change;

- initiation and maintenance of integrated monitoring systems for terrestrial and marine ecosystems;

- intensive assessment of water resources and water quality, especially in arid and semi-arid developing countries and their sensitivity to climate change;

- regional predictions of changes in soil moisture, precipitation, surface and subsurface runoff regimes and their interannual distributions as a result of climate change;

- assessment of vulnerability of countries to gain or loss of energy resources, particularly biomass and hydroelectric power in developing countries;

- adaptability of vulnerable human populations to heat stress and vector-borne and viral diseases;

- global monitoring of sea-level changes, particularly for island countries;

- identification of populations and agricultural and industrial production at risk in coastal areas and islands;

- better understanding of the nature and dynamics of ice masses and their sensitivity to climate change;

- integration of climate change impact information into the general planning process, particularly in developing countries; and

- development of methodology to assess sensitivity of environments and socioeconomic systems to climate change.

- Some of these topics are already being covered by existing and proposed programs and these will need continuing support. In particular, there are three core projects of the International Geosphere-Biosphere Program, namely:

  Land-Ocean Interactions in the Coastal Zone

  Biosphere Aspects of the Hydrological Cycle

  Global Change Impact on Agriculture and Society

  that will provide valuable data in the coming years.

Chapter 1
Scenarios used in the Report

Any changes which take place as the results of increasing emissions must be viewed against a background of changes which are already occurring and which will continue to occur as a result of other factors such as:

- Natural changes - these include long-term changes which are driven by solar and tectonic factors, and short-to-medium term changes which are driven by ocean and atmospheric circulation patterns.

- Population increase - the latest UN figures show that current world population is 5.3 billion, with a predicted growth to 8.5 billion by 2025 and then stabilising at more than 11 billion in the late 21st century; this growth will be unevenly distributed on a regional basis and will impact on already vulnerable areas, particularly in Africa and the Middle East.

- Land use changes - the clearing of forests for new agricultural production, together with more intensive use of existing agricultural land, will contribute to land degradation and increase demands for water resources.

In an ideal world, Working Group I would have had the time to produce scenarios for emission-induced climate change which could have been used as a basis for the analyses of this Working Group. However, this was precluded because work proceeded in parallel. As a result, and in order to complete its work in time, Working Group II has used a number of scenarios based on existing models in the literature.

The scenarios generally have the following features:

(i) an effective doubling of CO_2 in the atmosphere over pre-industrial levels between now and 2025 to 2050 for a 'business-as-usual' scenario, with no changes to present policy;

(ii) an increase of mean global temperature in the range 1.5°C to 4.5°C corresponding to the effective doubling of CO_2;

(iii) an unequal global distribution of this temperature increase, namely half the global mean in the tropical regions and twice the global mean in the polar regions;

(iv) a sea-level rise of about 0.3 to 0.5 m by 2050 and about 1 m by 2100, together with a rise in temperature of the surface ocean layer of between 0.2° and 2.5°.

These scenarios can be compared with the recent assessment of Working Group I which, for a 'business as usual' scenario, has predicted the increase in global temperatures to be about 1°C above the present value by 2025 and 3°C before the end of next century. However, it has estimated the magnitude of sea-level rise to be about 20 cm by 2030 and about 65 cm by the end of next century. Nevertheless, the impacts based on 1-2 m rise serve as a warning of the consequences of continued uncontrolled emissions.

The smaller rise docs not lessen the anxiety, for their continued existence, of the small island countries, particularly the Pacific and Indian Oceans and the Caribbean, or of the larger populations in low-lying coastal areas such as Bangladesh. It is difficult to predict the regional effects of sea-level rise with any certainty. Significant variations of sea-level already occur for a variety of reasons, while there are considerable shifts in land levels associated with tectonic plate movements which can also lead to rises and falls.

The scenarios of Working Group II are derived both from General Circulation Models and from palaeo-analog techniques. Palaeoclimate analogs are proposed by Soviet scientists as a means by which climate changes can be assessed. The methodology assumes that past warm geologic intervals provide insight into possible future climate conditions. The General Circulation Models, developed by Western scientists, are based on three-dimensional mathematical representations of the physical processes in the atmosphere and the interactions of the atmosphere with the earth's surface and the oceans. There is considerable scientific debate about the merits and demerits of each of these, as discussed in the report of Working Group I.

The palaeoclimate scenarios used by Soviet scientists are based on three warm geological periods with estimated future levels of concentration of CO_2

applied to them. The details of these are shown in Table 1.1. While these are superficially similar to the predictions of the General Circulation Model approach for different CO_2 concentrations, the factors which caused the climate changes in geologic times are not clear. Nevertheless, they have been used to make predictions of climate change of regions in the USSR.

The General Circulation Models are, in their current state of development, comparatively crude in their description of many of the processes involved. However they can be used to simulate regional changes resulting from a range of concentrations of CO_2 in the atmosphere. Working Group I has favoured the General Circulation Model approach in producing its predictions of temperature rise and precipitation changes. In its report, estimates for 2020 have been given for central North America, southern Asia, Sahel, southern Europe and Australia. These are reproduced in Table 1.2 and are broadly similar to those used by Working Group II.

Despite the current uncertainties, both techniques have been used by Working Group II in the development of regional impacts to assist policy makers. There are problems with prediction of regional precipitation since there is disagreement between various General Circulation Model outputs as a result of simplifications to the representation of complex physical processes. Current research is seeking to improve the General Circulation Model approach and to increase resolution to enable better regional predictions. There are also problems with the palaeoanalog approach which yields differing scenarios for precipitation from the General Circulation Model approach. This leads to different assessments of impact on water resources and agriculture. Soviet scientists are working to validate their techniques and improve regional scenarios.

It should be noted that, in many situations, the overall impact is determined more by the changes in the magnitude and frequency of extreme events than by changes in the average. This is especially the case for tropical storms and droughts. The assessment of Working Group I of possible climate changes suggests a low probability of increased frequency of extreme events. However, it is entirely possible that shifts in climate regimes will result in changes in frequency in certain regions.

An issue of importance not considered in any detail is the impact of possible response strategies (developed by Working Group III) on the scenarios used here. Thus, a major change in energy production from fossil fuel to nuclear or renewable energy sources could drastically alter our assessments. Further, changes in agricultural practice could dramatically alter yields of particular crops in certain regions. These impacts of response strategies require much additional work.

Despite all these uncertainties, it is possible to make assessments of potential impacts of climate change by considering the sensitivity of natural systems to significant variations. These are summarised in the following sections under: agriculture and forestry; terrestrial ecosystems; hydrology and water resources; human settlement, energy, transport, industry, human health and air quality; world ocean and coastal zones; seasonal snow cover, ice and permafrost.

Table 1.1 Palaeoclimate analogs used by Soviet scientists

Period	**Analog** (year)	**Temperature** (difference from present)	**Past CO_2 concn.** (ppm)	**Assumed CO_2 concn.** (ppm)
Holocene Optimum	2000	+1	280	380
Eemian Interglacial	2025	+2	280	420
Pliocene Optimum	2050	+4	500-600	560

Table 1.2 Estimates for regional changes by Working Group I
(IPCC Business-as-Usual scenario; changes from pre-industrial)

The estimates are based on high resolution models, scaled to give a global mean warming of 1.8°C consistent with the best estimate (2.5°C) of climate response to greenhouse gases. With the low estimate value of 1.5°C, these values should be reduced by 30%; with a high estimate of 4.5°C, they should be increased by 50%. Confidence on these estimates is low.

Central North America (35°-50°N 85°-105°W)
The warming varies from 2° to 4°C in winter and 2° to 3°C in summer. Precipitation increase range from 0% to 15% in winter, whereas there are decreases of 5% to 10% in summer. Soil moisture decreases in summer by 15% to 20%.

Southern Asia (5°-30°N 70°-105°E)
The warming varies from 1° to 2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5% to 15% in summer. Summer soil moisture increases by 5% to 10%.

Sahel (10°-20°N 20°W-40°E)
The warming ranges from 1° to 3°C. Area mean precipitation increases and area mean soil moisture decreases marginally in summer. However, there are areas of both increase and decrease in both parameters throughout the region, which differ from model to model.

Southern Europe (30°-50°N 10°W-45°E)
The warming is about 2°C in winter and varies from 2° to 3°C in summer. There is some indication of increased precipitation in winter, but summer precipitation decreases by 5% to 15%, and summer soil moisture by 15% to 25%.

Australia (12°-45°S 110°-155°E)
The warming ranges from 1° to 2° in summer and is about 2°C in winter. Summer precipitation increases by around 10%, but the models do not produce consistent estimates of the changes in soil moisture. The area averages hide large variations at the subcontinental level.

Chapter 2

Agriculture and forestry

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1 Introduction

1.1 Objectives and approach

The purpose of this chapter is fourfold: first, to identify those systems, sectors and regions of agriculture and forestry that are most sensitive to anticipated changes of climate;[1] second, to summarise the present knowledge about the potential socioeconomic impact of changes of climate on world agriculture and forestry; third, to consider the adjustments in agriculture and forestry that are most likely to occur (even if no policy responses were implemented);[2] finally, to establish research priorities for future assessments of impact.

This chapter gathers together many different types of information. It is a synthesis of all available published material, as well as unpublished government and non-government reports. It also draws on summaries of expert judgment concerning impacts in many regions that resulted from contact made with more than 100 scientists in 50 different countries.

1.2 Assumptions

1.2.1 Climatic scenarios

The scenarios used in the estimates of global warming effects on agriculture and forestry were based on both General Circulation Model (GCM) simulations at 2 x CO_2 climate and palaeoclimatic reconstructions. The GCM scenarios are described in detail in Working Group I Report. The analog scenarios used in Soviet studies at mid-latitude Northern Hemisphere agriculture impacts are based on climate reconstructions of three past warm epochs as discussed in Chapter 1.

Where reference is made to an equivalent doubling of atmospheric CO_2, this is taken to be 460 ppm in about the year 2030 (which is the current best estimate, Working Group I). This represents a ca 60% increase over pre-industrial levels because CO_2 comprises about 60% of estimated greenhouse gas (GHG) forcing.

1.2.2 Assumptions concerning technology and management

Since the effects of changes in climate will be felt progressively over time, though not necessarily in linear increments, it is necessary to assess these against an exposure unit that is itself changing (irrespective of climate change). The nature of this 'moving target' is difficult to describe with accuracy, primarily because of the relatively long time scales involved (eg 50-100 years). Changes in technology and management may, over that length of time, alter some aspects of agriculture and commercial forestry beyond recognition.

A common approach to this problem is, first, to estimate impacts as they might occur in the future, assuming technology and management as it is now; for example, assuming the extent of irrigation and fertiliser application to be as at present. Subsequent assessments then allow for possible developments in technology and management, identifying those adjustments necessary either to obviate major negative effects or to exploit positive ones. This distinction between 'impact experiments' and 'adjustment experiments' has been made in a number of previous impact assessments (see Parry and Carter, 1988).

In the present report, and unless otherwise stated, data on estimated impacts relate to changes in productive *potential* against a baseline of present-day base technology and management. However, likely *(actual)* effects on production must be measured against a realistic future reference base. In order to characterise this baseline certain assumptions must be made about changes in food and timber demand (on the basis of changes in population and per capita income), in use of inputs (particularly amount of fertiliser), in extent of the farmed and forested area and in many other aspects of agriculture and forestry which are likely to alter in the future even if climate did not change. These assumptions are consistent with UN and World Bank projections.

2 Potential impacts on agriculture and land use

2.1 Introduction

Owing to the many remaining uncertainties about possible future changes of climate (particularly changes in regional precipitation patterns and the rate of climate change over time) *no forecast can be*

1 Note impacts on fisheries are considered in Chapter 6 of IPCC Working Group II

2 Note technical adjustments which can reasonably be presumed to occur as a result of changes of climate are considered in this report Policy responses at the national and international level are evaluated in the report of the IPCC Working Group

made in this report concerning any specific impact on agriculture. It is possible, however, to identify what types of impacts might occur under a number of possible changes of climate and thus, by inference, what types of climate change could constitute a significant risk or benefit for agriculture. Four approaches can be adopted to achieve this end: (i) the identification *a prion* of the types of climate change most critical for agriculture; (ii) the identification of regions most at risk from such changes of climate; (Hi) the consideration of types of impact likely to result from climatic change; and, (iv) the evaluation of adjustments that are likely to occur in agriculture in response to such impacts or to the perception of their risk of occurrence. These four approaches will be followed, in turn, in this report.

2.2 Critical types of climatic change

The potentially most important changes of climate for agriculture, upon which there is some agreement by GCMs, include changes in climatic extremes, warming in the high latitudes, poleward advance of monsoon rainfall, and reduced soil water availability (particularly in mid latitudes in midsummer, and at low latitudes).

2.2.1 Climatic extremes

It is not clear whether temporal variances in temperature or precipitation will occur as a result of climatic change. However, even if variances remain the same as under the present climate, an increase in monthly or annual average temperatures will result in the increased frequency of occurrences of days with temperatures above particular thresholds. Changes in the frequency of distribution of precipitation is not as certain, but the combination of elevated temperatures and drought constitutes the greatest risk to agriculture in many regions from global climatic change.

2.2.2 Warming in high latitudes

There is relatively strong agreement among GCM predictions that warming will be greater at higher latitudes. This will reduce temperature constraints on high-latitude poleward agriculture, increase the competition for land here, and result in the northward retreat of the southern margin of the boreal forest (these possible effects are discussed in detail in Section 3.4.1). Warming at low latitudes, although less pronounced, is also likely to have a significant effect on agriculture.

2.2.3 Poleward advance of monsoon rainfall

In a warmer world the intertropical convergence zones (ITCZs) would be likely to advance further poleward as a result of an enhanced ocean-continent pressure gradient (itself the result of more warming of the land surface in the pre-monsoon season). If this were to occur - and it should be emphasised that this conclusion is based on GCM equilibrium experiments, and that the transient response could be different - then total rainfall could increase in some regions of monsoonal Africa, monsoonal Asia and Australia, though there is currently little agreement between GCMs on which regions these might be. Rainfall could also be more intense in its occurrence, so flooding and erosion could increase.

2.2.4 Reduced soil water availability

Probably the most important consequences for agriculture would stem from higher potential évapotranspiration, primarily due to the higher temperatures of the air and the land surface. Even in the tropics, where temperature increases are expected to be smaller than elsewhere, the increased rate of loss of moisture from plants and soil would be considerable. It may be somewhat reduced by greater humidity and increased cloudiness during the rainy seasons, but could be pronounced in the dry seasons.

At present we cannot be certain about the regional pattern of soil water changes that may occur. There are, however, regions in the world where the GCM predictions are in some agreement regarding such changes. The following is a summary of those regions where current 2 x CO_2 experiments by three GCMs (GISS, GFDL and NCAR) all project decreases in soil water (Kellogg and Zhao, 1988; Zhao and Kellogg, 1988; Schlesinger and Mitchell, 1985). It should be emphasised that coincidence of results for these regions is not statistically significant and that the evidence available at present is extremely weak. Moreover, the significance of decreases in soil water will vary considerably from region to region according to whether they occur during the growing or non-growing season.

i) Decreases of soil water in December, January and February

Africa: Horn of Africa[1], southern Africa[1], western West Africa[2]
Asia: western Arabian Peninsula, Southeast Asia

1 Note it should be emphasised that recent (and, in some cases, unpublished) GCM experiments do not produce drying in these regions
2 Note changes over western West Africa are small

Australasia: eastern Australia
North America: southern United States
South America: northern Argentina

ii) Decreases in soil water in June, July and August:

Africa: Maghreb, West Africa, Horn of Africa[1]
Europe: parts of Western Europe
Asia: north and central China, (including Mongolia); Soviet central Asia and parts of Siberia
North America: southwestern United States, and central America
South America: eastern Brazil
Australasia: western Australia

The regions identified above are those where soil water may decrease in an equilibrium climate for doubled equivalent CO_2. But different latitudes could approach equilibrium at different rates of change in temperature and rainfall because they include different amounts of land, which warms up faster than ocean. Thus the time-evolving patterns of soil water change could vary significantly from the equilibrium simulation. Moreover, the effects of climatic changes on agriculture are likely to be greater during periods of rapid change, before equilibrium is reached and before farming systems have had time to adapt to their altered environment. Despite these important caveats, we may conclude that there may be some regions where significant reductions in agricultural potential occur due to decreases in crop water availability. There is at present, however, little agreement as to which regions these will be.

2.3 Present-day vulnerability to climate

In addition to the unequal regional pattern of critical types of climatic change, there are important inequalities in the distribution of present-day vulnerability to climate. Since climate is the major factor limiting potential productivity at the global level, changes of climate are likely to have substantial effects on such limits. Insufficient temperature and rainfall are the main climatic limits which operate largely through the curtailment of the growing period. Overall, 63% of the land area of developing countries is climatically suited to rain-fed agriculture, but this endowment varies considerably between regions (FAO, 1984). It amounts to as much as 85% in South America, 84% in Southeast Asia, but is limited to 64% in Central America and 53% in Africa. The severest climatic limitations to rain-fed agriculture are to be found in Southwest Asia where 17% is too mountainous and cool, and 65% is too dry, leaving only 18% as potentially productive (FAO, 1984).

These climatic limits to agriculture, in combination with soil constraints (particularly shallowness, poor drainage and salinity) mean that the potential base for rain-fed agriculture is quite limited in certain regions. Any further curtailment of potential owing to changes of climate could severely strain the ability of many developing countries to feed their population.

Certain regions stand out as particularly vulnerable as a result of climatic and soil constraints on then-land base and their population requirements where, even with high levels of inputs, land resources cannot meet the needs of local populations. These occupy as much as 22% of the global land area and contain 11% of the population. Areas under greatest pressure, where there is a high degree of imbalance between population and land potential, are the cool and cold tropics (eg the Andean region, the Maghreb, the mountain regions of Southwest Asia), the Indian subcontinent, and parts of mainland and insular Southeast Asia.

2.4 Regions of risk

One means of identifying regions most at risk from climate change is to combine the two preceding analyses, noting those regions which (i) are regions where preliminary projections indicate decreases in soil water under equilibrium 2 x CO_2 climates and also which (ii) are regions identified as critically vulnerable in terms of their resource ability to support existing population. These regions at risk are:

Africa: Maghreb, West Africa, Horn of Africa, southern Africa
Asia: western Arabia, southeast Asia
North America: Mexico and Central America
South America: parts of eastern Brazil

2.5 Critical vulnerabilities in food trade

An additional set of regions that deserves particular attention includes the food-exporting countries, which are the source of most of the world's traded cereals. Here, substantially adverse or beneficial changes of climate could markedly affect the amount of traded food and its price. A key role in the world food system is played by a few food-exporting countries, with only 21 out of 172 countries in the world currently being net exporters of cereals. In 1987, 77% of all traded cereals derived from only three countries.

The major food-producing countries, because of their key role as holders of large food stocks, are doubly important to the world food system. In 1988-

89 the US, Canada and European Community held almost one-third of the world's stock of wheat and coarse grain (mainly maize, sorghum and barley). The US held 17% of wheat and 47% of maize.

In addition, it should be noted how sensitive world food security remains to variations in weather. To illustrate, in 1987-88 world wheat and coarse grain stocks stood at 353 million tonnes (mt), but fell to 248 mt in 1988-89 and are estimated to be 249 mt in July 1989 (International Wheat Council, 1989). Most of this fall is attributable to reductions in stock in North America due to the 1988 heatwave and drought in the Great Plains and Corn Belt. Closing stocks of wheat in the US fell from 49 mt in 1986-87, to 34 mt in 1987-88 and to 17 mt in 1988-89. Thus factors affecting stocks in North America also affect world food stocks and prices.

These 'breadbasket' countries are critical to the world food system, being regions where relatively small percentage changes in production due to changes of climate could have severe impacts on the quantity, price and type of food products bought and sold on the world food market.

The following list summarises those regions and countries which are both net food exporters and for which there is some agreement between GCMs regarding reductions in soil water under 2 x CO_2 climates:

Europe: parts of Western Europe
North America: southern US
South America: northern Argentina
Australasia: western Australia.

2.6 Potential effects on agriculture and land use

2.6.1 Types of effect

Three types of effect of climatic change on agriculture are considered in this report: (i) the physiological ('direct') effect of elevated levels of atmospheric CO_2 on crop plants and weeds, (ii) the effect of changes in parameters of climate (eg temperature, precipitation and solar radiation) on plants and animals, and (iii) the effects of climate-related rises in sea-level on land use (considered in section 2.8)

2.6.2 'Direct' effects of elevated CO_2 and other greenhouse gases

Considerable basic physiological information is now available from a large number of studies showing that increases in ambient CO_2 have diverse and profound effects on plant growth. These effects of elevated CO_2 can be experimentally demonstrated with concentration increases in the upper end of the range expected to occur by the middle of next century. The major effects are on photosynthesis and respiration and thereby on growth (the accumulation of dry matter), and there are additional effects of increased CO_2 on development, yield quality and stomatal aperture and water use (see Gifford, 1988; Morison, 1989).

i) Photosynthesis, respiration and growth

In general, as photosynthesis is the net accumulation of carbohydrates formed by the uptake of CO_2, increased CO_2 results in increased photosynthesis. A doubling of CO_2 increases the instantaneous photosynthetic rate by 30% to 100%, depending on the other environmental conditions (Pearcy and Bjorkman, 1983). The balance between the photosynthetic gain and loss of carbohydrate from plants by respiration is the resultant growth. Unfortunately, the response of respiration to CO_2 has been little studied and there are suggestions that respiration could be lower rather than higher owing to a changed carbohydrate status (Bunce, 1989). This process may underlie some of the unexpectedly high responses of growth to increased CO_2 that have been observed. Within single species there are differences in responsiveness between different varieties and genotypes, differences that offer the possibility of breeding for optimum advantage with increased CO_2. In order to take full advantage of such opportunities these varieties and genotypes must be identified now.

In the overwhelming majority of cases the effect of CO_2 on productivity has been shown to be beneficial - if all other factors are maintained constant - and a 10-50% increase in dry matter accumulation can occur in most species with a doubling of ambient CO_2 concentration. In a summary of 770 studies the mean mature yield increase for C3 crops (see below) was 26% but the extremes ranged from a decrease of 20% to an increase of 200% (Kimball, 1983). For temperate cereals the mean increase observed in grain yield was 36%. The large range in effect of CO_2 can, to some extent, be attributed to species differences, however few realistic studies under comparable conditions have been made.

Part of the variation in results can also be attributed to interaction with other environmental conditions, which is clearly of importance as increased CO_2 will occur in combination with changes in temperature, rainfall etc. A doubling of CO_2, for example, in addition to increasing net photosynthesis in C3 plants at a fixed temperature, also increases the optimum temperature for photosynthesis by about

4°-6°C (Acock and Allen, 1985; Osmond et al., 1980; Jones, 1986). This may appear to be of considerable advantage in warmer climates, but the optimum range of temperature for photosynthesis also narrows. In present conditions temperature has relatively little effect over a broad range for most plants growing in the habitats to which they are currently adapted. Under elevated levels of CO_2, photosynthesis and, by inference, growth rate, may therefore become more variable as temperature conditions vary.

The interactions with other environmental conditions are critical in determining the net effect of increased CO_2. In particular, it has been demonstrated that in adverse conditions (eg nutrient limitation, water shortage, salinity, cool temperatures and air pollution) the relative effect of increased CO_2 is larger than under optimal conditions (Morison, 1988; Warrick et al., 1986). Indeed, increased CO_2 could improve growth sufficiently to make saline and polluted environments more productive though, as with all of these interactions, insufficient data exist to produce quantitative predictions. Another environmental interaction for which few, if any, studies have been completed is the combined effect on agriculture of acidic depositions and GHG-induced changes.

ii) C3 and C4 plants

Two groups of plants differ in their fundamental carbon fixation biochemistry - the C3 and C4 groups. It is widely accepted that the response of growth to elevated CO_2 in C3 plants (eg wheat, rice, barley, root crops, legumes) is larger than that of C4 plants (eg maize, sorghum, millets, sugarcane). It has been estimated that the average effect of doubled CO_2 concentration on wheat grain yield is an increase of 35% (from eight studies, Cure, 1985) while that on maize has not been adequately quantified (Cure, 1985). Most crops grown in cool, temperate or moist habitats are C3 plants, as are all trees. The C3 group therefore accounts for most of the world's plant biomass.

Although C4 crops account for only about one-fifth of the world's food production they are a particularly important source of world food in the tropical regions. Maize alone accounts for 14% of world food. Moreover, many pasture and forage grasses worldwide are C4 including important prairie grasses in the US and in the subtropics and tropics (Edwards and Walker, 1983).

In addition, 14 of the world's most troublesome 17 terrestrial weed species are C4 plants in C3 crops (Morison, 1989). The difference in response to CO_2 may make such weeds intrinsically less competitive, but the final outcome will depend on the relative response of crop and weed to climatic changes as well. C3 weeds in C4 crops may increase as a problem.

Changes in relative crop performance may force changes in areas sown, for example increasing areas of soybean and reducing areas of maize. This may accelerate the existing trend in the third world countries to replace C4 crops with C3 as a response to the promise of high-yielding varieties of wheat, rice and barley. For example, in the last 20 years in India there has been a reduction in the production of C4 crops from 40% to only 23% of the total cereal production. Conversely, it may counteract the current poleward expansion in the temperate zone of grain maize which would otherwise follow increases in global temperature. Similarly, it may reverse the current trend away from perennial rye-grass (C3) towards silage maize as the major forage product in temperate zones (Jones, 1986). Another probable area of impact will be on sugar production, reducing further the value of the sugar-cane crop (C4) in tropical countries relative to the success of sugar beet in the temperate zone.

A third biochemical group of plants that is locally important in the arid zone are those with CAM metabolism (Crassulacean Acid Metabolism), which includes many plants in the cactus family, the *Crassulaceae* and desert succulents. The species in this group of major commercial importance are sisal and pineapple. These plants will show little or no response to increased CO_2, thus eroding their competitive advantage over common C3 weeds and reducing yields relative to C3 crops.

Hi) Plant development

Some developmental processes such as flowering have also been shown to be affected by elevated CO_2 in both positive and negative directions, although this has not yet been widely studied (Morison, 1989). If the developmental process is affected then the progress of the crop through the different stages of the life cycle is altered, thus potentially shortening or lengthening the required growing period. In temperate zones this may mean decreases or increases in yield, respectively, but in seasonally arid areas any lengthening of the required growing season is generally associated with increased drought risk. Since many of the advances in cropping in such areas have been due to the introduction of shorter duration varieties, the developmental response of the crops of these areas urgently needs to be examined. As with the other processes affected by CO_2, genetic variation in responsiveness is evident and could prove amenable for selection by traditional and modern breeding methods.

iv) Yield quality

The amount of information available on the effect of increased CO_2 on quality is very small compared to that on dry matter production. Some changes in composition of crop tissue have been noted, though much remains to be done. Generally, there is a rise in the total non-structural carbohydrate content (starch and sugars) with increase in CO_2 concentration (Bazzaz et al., 1985; Strain, 1985). This is particularly the case at low temperatures. For fruits, grains and vegetables this change in carbohydrate status may affect palatability, nutritional value and taste, as well as storage qualities.

Nitrogen content of leaf, stems and fruits is generally reduced by high CO_2. This has been clearly demonstrated in species as diverse as white oak, soybean, *Echinochloa* (a C4 grass), wheat, cotton, lettuce and cucumber. This implies reduced protein levels and reduced nutritional value for livestock, pests and disease organisms and humans. Over the last 40 years there has been a 1-to-l relationship between nitrogen applied to wheat crops in the UK and the nitrogen taken off in the grain and straw (Austin, 1988). With increased CO_2 the same yield may be produced with less nitrogen fertiliser application. However, the bread-making quality of the grain may be diminished unless there are changed management and varieties to counteract this effect.

Further, in the very few experimental studies carried out, pest herbivory was altered under conditions of high CO_2: more leaves were eaten but individuals were smaller with probable reductions in population growth. Changing the carbon to nitrogen and carbon to phosphorus ratio of plant material also has consequences on the decomposition processes in agricultural and forest soils, leading to reductions in decomposition rates and decreases in ecosystem productivity (Dahlman et al., 1985).

v) *Stomatal aperture and water use*

Increases in atmospheric CO_2 reduce the water requirements of plants by reducing transpiration (per unit leaf area) through reductions in stomatal aperture. A doubling of CO_2 causes partial stomatal closure in both C3 and C4 plants (approximately a 40% decrease in aperture, Morison, 1987). In many experiments this results in reductions of transpiration of about 23% to 46% (averages compiled by Cure and Acock, 1986; Kimball and Idso, 1983). However, there is considerable uncertainty over the magnitude of this effect in natural conditions. Many calculations of evaporation have relied on the Penman-Monteith model for evaporation which includes meteorological and vegetation variables in a sound mechanistic framework. However, its use in predictions is limited as the variables are not independent of each other. At the level of single leaves the evaporation rate affects the leaf temperature, which affects the net radiation, to an extent dependent on the degree of 'coupling' of leaf to the air around it (Morison, 1985 and 1989). There is additional feedback in whole canopies between the humidity in the canopy and the evaporation rate from the plant and the soil surface (Morison, 1989; McNaughton and Jarvis, 1983; Goudriaan, 1989). Further, at the regional scale, the temperature and humidity conditions in the mixed planetary boundary layer are also dependent on the heat and vapour transfer from the vegetation surface. The extent of these feedbacks varies with the microclimatic and vegetation conditions so that predictions of changes in evaporation rates with changed climate and increased CO_2 vary considerably both in magnitude and sign. In addition, increased growth results in greater leaf area so the total water use per plant in high CO_2 may be similar to that in present concentrations (Gifford, 1988), although for complete vegetation stands the changes in leaf area index may change the whole pattern of energy exchange at the surface. The net effect is likely to be small for short, dense, extensive crops and more important in sparse and tall vegetation in semi-arid areas.

vi) Effect on biological nitrogen fixations

Increased levels of CO_2 can enhance nitrogen fixation by leguminous species, through increased rates of photosynthesis. Many C4 species harbour nitrogen-fixing bacteria such as *Axospirullum* and *Azatobactor* in their rhizosphere which contribute to nitrogen fixation and support growth at low nitrogen contents of the soil. The direct effects of CO_2 on nitrogen fixation could be advantageous in grass and legume pastures. However, increased temperature can reduce nitrogen fixation and also increase the energy cost of nitrogen fixation. At what temperature the beneficial effects of CO_2 would be counteracted is difficult to predict, but the existing strains of *Rhizobium* which are adaptable at low temperature may require replacement for deriving the potential benefits of enhance CO_2. This would also apply to many tree species which fix nitrogen through rhizobial and non-rhizobial symbiosis. However, limiting water conditions could impair these effects. More research in this important area is needed.

vii) Effects of increases in other greenhouse gases

The other GHG contributing to the greenhouse effect are methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3) and halocarbons (CFCs). Carbon monoxide is also involved as it exerts strong control over the chemistry of the troposphere and lower stratosphere and affects the concentration of the GHG.

Methane and nitrous oxide are both products of agricultural systems, the former from anaerobic respiration in rice paddies and animal rumens, and the latter from denitrification (oxidation) of soil nitrate by bacterial respiration. However, there is no evidence that atmospheric concentrations of these gases will lead to direct effects on animals or plants. Other pollutant oxides of nitrogen (NO and NO_2 occur at lower concentrations and can cause crop damage at concentrations in the ppb range such as typically arise from local sources of fossil fuel combustion.

Carbon monoxide does not affect plants, and a major sink for carbon monoxide produced by fossil fuel burning is soil uptake and microbial oxidation. In humans and presumably in other mammals used in agriculture the concentrations at which health is affected start at 10-50 ppm, whereas atmospheric concentrations are in the range of 100 ppb, ie 100-500 times lower (Wellburn, 1988).

Halocarbons have no direct effects on plants or animals at atmospheric concentrations.

Ozone is a potent inhibitor of plant growth and has effects on animal health. The US Health Standard requires that an hourly mean of 120 ppb should not be exceeded more than once a year. In practice during photochemical smog episodes in industrial areas, concentrations exceed these levels frequently, for several days at a time. However, these are local episodes related to strong local sources of pollutants and are not global means. Surface monitoring stations suggest annual average background concentrations of 15-30 ppb (Penkett, 1988) in the troposphere. A large amount of experimental evidence has shown that filtering air of normal pollutant concentrations of O_3 can enhance crop growth. For example, removal of mean seasonal concentrations of 80 ppb in the southeast US can enhance crop yield by 10-50% (Heck et al., 1982). Any further increases in troposphere O_3 will there-fore add to this damage.

2.6.3 Effects of changes in climate

i) Introduction

This section discusses those effects on agriculture that may occur as a result of GHG-induced changes of climate. Consideration is given, in turn, to (i) effects on agroclimate, (ii) effects on pests and diseases, (iii) effects on other aspects of the agricultural environment such as soils, (iv) effects on crop yields and livestock and (v) effects on agricultural production.

ii) Effects on agroclimate

Shifts of thermal limits to cropping Increases in temperature can be expected to lengthen the growing season in areas where agricultural potential is currently limited by insufficient warmth, resulting in a poleward shift of thermal limits of agriculture. The consequent extension of potential will be most pronounced in the northern hemisphere because of the greater extent here of temperate agriculture at higher latitudes.

An indication of the extent of shift is given by the relocation of critical levels of effective temperature sums (accumulated temperatures) for cropping in northern regions. Taking 1300 day-degrees (above a base of 5°C as the southern limit of the boreal zone, and thus as a proxy northern limit of arable agriculture, this limit shifts about 500-1000 km northwards under the 2 x CO_2 equilibrium climate simulated by the GISS GCM (Kauppi and Posch, 1988).

There may, however, be important regional variations in our ability to exploit this shift. The greater potential for exploitation of northern soils in Siberia than on the Canadian Shield, may mean relatively greater increases in potential in northern Asia than in northern North America (Jager, 1988).

A number of estimations have been made concerning the northward shift in productive potential in mid-latitude northern hemisphere countries. These relate to changes in the climatic limits for specific crops under a variety of climatic scenarios, and are therefore not readily compatible (Newman, 1980; Biasing and Solomon, 1983; Williams and Oakes, 1978; Parry and Carter, 1988; Parry et al., 1989). They suggest, however, that a 1°C increase in mean annual temperature would tend to advance the thermal limit of cereal cropping in the mid-latitude northern hemisphere by about 150-200 km; and to raise the altitudinal limit to arable agriculture by about 150-200 m.

While warming may extend the margin of potential cropping and grazing in mid-latitude regions, it may reduce yield potential in the core areas of current production, because higher temperatures encourage more rapid maturation of plants and shorten the period of grain filling.

An important additional affect of warming, especially in temperate and mid-latitudes, is likely to be the reduction of winter chilling (vernalisation). Many temperate crops require a period of low temperatures in winter to either initiate or accelerate the flowering process. Low vernalisation results in low flower bud initiation and, ultimately, reduced yields. A 1°C warming would reduce effective winter chilling by between 10% and 30%, thus contributing to poleward shift of temperate crops (Salinger, 1989).

Increases in temperature are also likely to affect the crop calendar in low-latitude regions, particularly where more than one crop is harvested each year. For example, in Sri Lanka and Thailand a 1°C warming would probably require a substantial rearrangement of the current crop calendar which is finely tuned to present climatic conditions. (Kaida and Surareks, 1984; Yoshino, 1984).

Shifts of moisture limits to agriculture There is much less certainty about GHG-induced changes in rainfall than there is about temperature - not only concerning the magnitude of change, but also its spatial pattern and its distribution through the year. For this reason it is difficult to identify possible rainfall-induced shifts in the climatic limits to agriculture. This is particularly so because relatively small changes in the seasonal distribution of rainfall can have disproportionately large effects on the viability of agriculture in tropical areas, largely through changes in growing period when moisture is sufficient and thus through the timing of critical episodes such as planting etc. However, regions where changes in average rainfall may have the most pronounced effect have been outlined in Section 2 (above).

Regions affected by drought, heat stress and other extremes Probably most important for agriculture, but about which least is known, are the possible changes in measures of climatic variability, such as the magnitude and frequency of drought, storms, heatwaves and severe frosts. Some modelling evidence suggests that hurricane intensities will increase with climatic warming (Emanuel, 1987). This has important implications for agriculture in low latitudes, particularly in coastal regions.

Since crop yields often exhibit a non-linear response to heat or cold stress, changes in the probability of extreme temperature events can be significant (Mearns et al., 1984; Parry, 1976). In addition, even assuming no change in the standard deviation of temperature maxima and minima, we should note that the frequency of hot and cold days can be markedly altered by changes in mean monthly temperature. To illustrate, under the GISS 2 x CO_2 scenario the number of days in which temperatures would fall below freezing would decrease from 39 to 20 in Atlanta, Georgia (US), while the number of days above 90°F would increase from 17 to 53 (EPA, 1989). The frequency and extent of area over which losses of agricultural output could result from heat stress, particularly in tropical regions, is therefore likely to increase significantly. Unfortunately, no studies have yet been made of this. The apparently small increases in mean annual temperatures in tropical regions (ca 1° to 2°C under a 2 x CO_2 climate) could sufficiently increase heat stress on temperate crops such as wheat that these are no longer suited to such areas. Important wheat-producing areas such as Northern India could be affected in this way.

There is a distinct possibility that, as a result of high rates of evapotranspiration, some regions in the tropics and subtropics could be characterised by a higher frequency of drought, or a similar frequency of more intense drought than at present. Current uncertainties about how regional patterns of rainfall will alter, mean that no useful prediction of this can at present be made. However, it is clear in some regions that relatively small decreases in water availability can readily produce drought conditions. In India, for example, lower-than-average rainfall in 1987 reduced food grains production from 152 mt to 134 mt, lowering food buffer stocks from 23 to 9 mt. Changes in the risk and intensity of drought, especially in currently drought-prone regions, represent potentially the most serious impact of climatic change on agriculture both at the global and the regional level.

Hi) Effects on the distribution of agricultural pests and diseases

Studies suggest that temperature increases may extend the geographic range of some insect pests currently limited by temperature (EPA, 1989; Hill and Dymock, 1989). As with crops, such effects would be greatest at higher latitudes. The number of generations per year produced by multivoltine pests (such as the European red mite and two-spotted mite in New Zealand) would increase, with earlier establishment of pest populations in the growing season and increased abundance during more susceptible stages of growth (Salinger, personal communication, 1989b). An important unknown, however, is the effect that changes in precipitation amount and air humidity may have on the insect pests themselves and on their predators, parasites and diseases. Climatic change may significantly influence interspecific interactions between pests and their predators and parasites.

Under a 2 x CO_2 climate there would be an increase in the over-wintering range and population density of a number of important agricultural pests in the US, such as the potato leafhopper which is a serious pest of soybeans and other crops (EPA, 1989). Assuming planting dates did not change, warmer temperatures would lead to invasions earlier in the growing season and probably lead to greater damage to crops. In the US Grain Belt increased damage to soy-beans is also expected due to earlier infestation by the corn earworm.

Examination of the effect of climatic warming on the distribution of livestock diseases suggests that those at present limited to tropical countries, such as Rift Valley fever and African swine fever, may spread, causing serious economic losses (EPA, 1989). The geographic distribution and activities of other diseases already important in the US may also expand. The horn fly, which currently causes losses of $730.3 million in the US beef and dairy cattle industries might extend its range under a warmer climate leading to reduced gain in beef cattle and a significant reduction in milk production (Drummond, 1987; EPA, 1989). In the 1960s and 1970s a combination of the increased resistance of ticks to insecticides and the high costs of dipping threatened the profitability of the Australian beef industry. Prolonged summer rainfall and an extended developmental season, or conversely prolonged dryness leading to increased nutritional stress in the host, are likely to cause heavy infestations (Sutherest, 1987). If such climatic conditions were to prevail in the future it is likely that ticks could become an increasing problem.

'New* or migrant pests may become established as climatic conditions become more favourable for them. In New Zealand there is the possibility of incipient swarming of locusts now developing in the Northland (Messenger, 1988) which may be an indication of climatic changes (Hill and Dymock, 1989). Indeed favourable climatic conditions in 1986-88 led to locust swarms reaching new limits in southern Europe (Pedgley, 1989).

In temperate regions, where insect pests and diseases are not generally serious at present, damage is likely to increase under warmer conditions. In Iceland, for example, potato blight currently does little damage to potato crops, unlike in warmer regions, being limited by the low summer temperatures. However, under a 2 x CO_2 climate that may be 4°C warmer than at present, crop losses to disease may increase to 15% (Bergthorsson et al., 1988).

Most agricultural diseases have greater potential to reach severe levels under warmer conditions. Fungal and bacterial pathogens are also likely to increase in severity in areas where precipitation increases (Beresford and Fullerton, 1989). Under warmer and more humid conditions cereals would be more prone to diseases such as Septoria. Also, increases in population levels of disease vectors may well lead to increased epidemics of the diseases they carry. An example would be increases in infestations of the Bird Cherry aphid *(Rhopalosiphum padi)* or Grain aphid *(Sitobian avenae)* leading to increased incidence of Barley Yellow Dwarf virus in cereals.

iv) Indirect effects on agriculture through effects on other environmental processes

There are numerous other paths by which changes in climate can have an indirect but important effect on agriculture, largely through concurrent effects on other physical systems.

Probably the most important, but about which we currently know little, is the effect on water resources for irrigation, particularly through changes in snow fall, spring snowmelt and groundwater recharge. In mid-latitude, mid-continental areas there are indications that reduced amounts of rainfall and snow fall could significantly reduce rates of groundwater recharge thus increasing rates of groundwater depletion. This could be the case, for example, with the Ogallala aquifer in the central US (EPA, 1989). In tropical regions, particularly areas of monsoon rainfall, increased intensity of rainfall could result in more runoff, but no increase in percolation or less available water in spite of increases in total rainfall amount. A similar effect could occur in some currently maritime mid-latitude regions, such as northwest Europe, where higher temperatures may result in a larger proportion of the total rainfall occurring from convective thunderstorms, with consequent increased intensity of rainfall, increased runoff and reduced percolation (Beran and Arnell, 1989).

Changes in the intensity of rainfall may affect rates of soil erosion and desertification. In addition, higher rates of évapotranspiration could, in some regions, lead to more frequent spells during which topsoils are dry and therefore prone to erosion by wind. In Saskatchewan, for example, the frequency of moderate and extreme droughts is estimated to increase threefold under the GISS 2 x CO_2 scenario, with significant changes in the potential for wind erosion (Williams et al., 1988).

In major parts of the world where rain-fed agriculture is practised, the premium on soils with a large available water capacity may increase, because of the expected change to higher ET rates and greater variability in rainfall. This emphasises the need for sound land husbandry practices incorporating effective soil conservation.

A third, and more long-term, consequence of changes in rainfall may be changes in soil fertility resulting from changes in soil base status. In regions where rainfall increases, there may be an increased tendency for soil leaching and consequent reductions of fertility. For example, it has been estimated that soil fertility in the Leningrad region of the USSR could fall by more than 20% by the year 2035 as a result of rainfall increases and in spite of assumed trended increases in fertiliser application (Pitovranov et al., 1988a).

v) *Potential effects on crop yields and livestock productivity*

The following is a summary of current estimations, both published and unpublished, of the potential effects of climate change on crop and livestock productivity for different regions of the world. It should be emphasised that such potential effects are those estimated assuming present-day management and technology. They are not the estimated actual effects, which depend on how farmers and governments respond to the altered potential through changes in management and technology.

Unless otherwise stated the following estimates are for climates described by 2 x CO_2 GCM experiments. Also, unless otherwise stated, they are based on quantitative results from experiments with crop response models, not qualitative estimations derived from expert judgment.

North America
US: warming of 3.8° to 6.3°C, with soil moisture reduced by 10% (which is consistent with the GISS and GFDL 2 x CO_2 climate) is estimated to decrease potential yields of maize allowing for the limited beneficial fertilising effect of enhanced CO_2 on this C4 plant, by about 4-17% in California, 16 to 25% on the Great Plains (assuming irrigation), and by 5-14% in the southeast (also assuming irrigation) (EPA, 1989). In the Great Lakes region there could be a small increase in potential yields, depending on available moisture. Potential wheat yields decrease in the southern and central Great Plains, even with the beneficial direct effects of enhanced CO_2. Some northward shift of productive potential is evident. On average, over the region, dryland wheat yields decrease by 2-3%, and irrigated yields increase by 5 to 15% (EPA, 1989). Dryland soybean yields show a wide range of decreases from -3% in the Great Lakes region to between -24% to -72% in the southeast. Irrigation could offset much of these potential losses.

Canada: a warming of 3°-4°C, accompanied by reduced soil moisture consistent with the GISS 2 x CO_2 climate, is estimated to decrease yields of spring wheat nationally by about 19%, with regional variations from ca 18% in Saskatchewan, to ca 10% in Manitoba, to a small increase near the current northern limit of production (Williams et al.,1988; Smit, 1989). An expansion of wheat into the Peace River District might be possible, though elsewhere soils and terrain would continue to limit agriculture. Winter wheat would probably be better able to withstand an increased frequency of spring and early summer drought and might expand its area at the expense of spring varieties (though its yield is also expected to decline by about 4%). Yields of grain corn, barley, soybeans and hay are expected to decline in all but the northern part of Ontario (Smit, 1989). There would also be a decrease in yields of potatoes and forage crops in most regions of Canada.

Central and South America
Mexico and Central America: a warming of 3.3° to 5.4°C (consistent with 2 X CO_2 GCM projections) combined with either increases or decreases in rainfall (-23% to +3% depending on GCM) are likely to produce warmer, drier conditions and reductions in soil moisture of 10-20%. This could result in decreases in yields of maize and other rain-fed crops (of 5% to 25%), and, combined with heat stress and irrigation water scarcity, decreases in yields of major irrigated crops such as wheat (-Liverman, personal communication, 1990). If there were increases in rainfall, particularly rainfall intensity, this could lead to enhanced rates of soil erosion and consequent long-term loss of productive potential (Ramirez, personal communication, 1989).

Brazil: in the most vulnerable region of Brazil, the northeast, much depends on whether increases in precipitation are sufficient to compensate for increased potential évapotranspiration due to higher temperatures. An insufficient increase in rainfall is likely to lead to a serious decline in yield potential. For example, short-term rainfall decreases in the El

Nino years 1982-83 reduced total agricultural production in northeast Brazil by almost a quarter (Magalhaes, et el., 1988).

More precipitation in the centre-west would probably increase productivity in soybeans and, in the south, of wheat. A reduction in the frequency of frosts would decrease the risks in citrus and coffee production in the south (Magalhaes, personal communication, 1989).

Argentina, Chile and north Andean region: according to 2 x CO_2 GCM experiments, rainfall is projected to increase in currently moist areas and decrease in the semi-arid areas in the rain shadow of the Andes.

Increases of 2°-4°C would increase évapotranspiration by at least 10%, possibly leading to a drying of the Pampas. Cattle raising might become less productive (Salinger, 1989a). In the more maritime climate of Chile, increased winter precipitation could counter the small increases in évapotranspiration more than in Argentina. Grass production and cattle raising would probably stand to gain most in the centre and south. At high levels in the Andes, where cultivation limits are constrained by winter minimum temperatures, a 1°C warming would raise limits by ca 200 m (3800 m to 4000 m in central Ecuador) (Bravo et al., 1988). Increases in rainfall would probably lead to decreases in yields of barley but increases in those of potatoes.

Europe

Northern Europe: agriculture in Fennoscandia stands to gain from global warming more than perhaps any other region of the world. For example, in Finland, where the equilibrium 2 x CO_2 climate is projected to be ca 4°C warmer and also wetter than at present, yields of adapted cultivars of spring wheat are estimated to increase by about 10% in the south, up to 20% in central Finland, and more near the current northern limit of wheat. Yields of barley and oats are raised by 9-18%, depending on the region in Finland (Kettunen et al., 1988). In Iceland the carrying capacity of improved grassland for sheep is estimated to increase by about two-and-a-half times, and on unimproved rangeland by more than a half (Bergthorsson et al., 1988).

Northwest Europe: in the more maritime areas of this region (eg Ireland, UK, northern France, Netherlands, Belgium, Denmark) yields of indeterminate crops such as grass and potatoes would tend to increase under higher growing season temperatures, assuming sufficient increases in precipitation to counter higher rates of évapotranspiration. To illustrate, under a warming of ca 3°-4°C, grass yields in the Netherlands may increase by about 10% (Klijn et al., 1987) and potato yields in the UK by 50-75% (Squire and Unsworth, 1988). In addition, some crops which are now barely profitable to grow because of inadequate summer warmth (such as grain maize in the southern UK) may extend their profitable range several hundred kilometres further north (Parry et al., 1989). The yields of determinate crops such as wheat would, however, decrease with increasing temperatures - though in C3 crops these would be partly compensated by the direct effect of enhanced CO_2. In the UK it is estimated that the beneficial direct effect of doubled ambient atmospheric CO_2 on yields of winter wheat would be completely offset by the adverse effect of a mean annual temperature increase greater than 4.5°C (Squire and Unsworth, 1988).

Southern Europe: in the Mediterranean region quite substantial decreases in productive potential could occur if the GCMs are correct in predicting decreases in soil moisture in the summer, and possibly also in the winter months. Under a warming of 4°C and with annual rainfall reduced by >10% (the BMO 2 x CO_2 climate), biomass potential in Italy and Greece is projected to decrease by 5% and 36% respectively (Santer, 1985). In general there is a quite striking contrast between the increases in biomass potential in northern Europe and decreases in southern Europe that are implied by current GCM projections of GHG-induced changes in temperature and rainfall. This suggests an important northward shift of the balance of agricultural potential in the European Community.

Alpine Europe: in the European Alps a 1°C warming can be expected to raise climatic limits to cultivation by ca 150 m, (Balteanu et al., 1987) and a 4°C warming of the order projected for a doubling of atmospheric CO_2, would probably raise climatic zones in the Alps by 450-650 m, which would then be similar to the levels of those today in the Pyrenees which lie 300 km south of the Alps (Balteanu et al., 1987).

USSR and mid latitudes, Northern Hemisphere: Previous studies using the 2 x CO_2 GISS scenario assessed impacts on winter wheat, maize, rye, barley, oats, potatoes and green vegetables (Pitovranov et al., 1988a; Pitovranov et al., 1988b), but the most detailed current assessment is based on palaeoclimatic analogs.

The impact on potential crop productivity of three palaeoclimatic scenarios (Holocene Optimum, Eemian Interglacial, and Pliocene Optimum) was gauged including estimates of the direct effect of increased CO_2 concentration (Koval et al., 1983;

Mendzhulin et al., 1987; Mendzhulin, personal communication, 1989). The results of these studies for the mid latitudes of the Northern Hemisphere indicate that with 1°C of warming (ca 2000) there would be regional differences in moisture conditions, leading to a decrease in potential productivity in the drier parts of the mid-latitudes. This decrease in potential productivity may well be within the current limits of agricultural adaptation to climate variations. The Eemian and Pliocene palaeoanalog studies indicate improved moisture conditions which together with the beneficial effects of CO_2 enhancement were estimated to result in increased potential productivity of C3 crops.

A further set of calculations was made based on an empirical analysis of historical yield data to estimate the year-to-year variability of wheat yields for the three palaeoanalogs (Mendzhulin et al., 1985,1987), This study showed that in the Holocene analog (through the early part of the next century) a small increase in yield variability may occur in a number of mid-latitude regions. With global warming of 1°C yield variability for less favourable North American grain regions was estimated to be equivalent to the present-day yield variability of the most favourable grain region of the USSR (the Krasnodar region). With further warming corresponding to the Eemian Interglacial (+2°C by 2030) and subsequently the Pliocene Optimum (+3° to 4°C by late in the 21st century) the year-to-year yield variability was estimated to decrease in all mid-latitude grain regions of the Northern Hemisphere.

A regional study by Abashina and Sirotenko (1986) and Sirotenko et al. (1984 and in press) for each administrative unit of the European USSR used a dynamic model of productivity for various crops (Sirotenko, 1981). These studies considered the changes in surface biomass and the yield of some C3 grain crops for several levels of soil fertility for the Holocene and Eemian scenarios. For warming up to 1°C (up to 2000) there were regional variations in agroclimatic potential: a decrease of 5-10% was estimated for the steppe and forest-steppe zones of the USSR and an increase of up to 8% was found for the non-chernozem zone. With further warming, agroclimatic potential was estimated to increase by 5-10% in all but two regions of the European USSR for a warming of 1°C (after 2000) and by 10-20% with warming of 2°C (ca 2030).

Middle East

Few estimations of possible impacts have been completed for this region. Projected changes include an increase in temperature of ca 3.5°C and possible decreases in rainfall (of perhaps 0.5 mm per day, although this is very uncertain). Evidence from experiments in Israel indicate that under these changes of climate wheat yields would be reduced by up to 40% (Van Diepen et al., 1987).

Smaller increases in temperature (eg of 1°C) are estimated to decrease barley yield by ca 5% and any corresponding reduction in rainfall could result in decreases in excess of 20% without additional irrigation (evidence for Cyprus from Pashiardis and Michaelides, 1989).

Africa

Maghreb: assuming an increase in annual temperature of 1.5°C, évapotranspiration would increase by more than 10%, leading (without) any change in rainfall) to a decrease in river flow of more than 10% (Salinger et al., 1989a). The likelihood is that the irrigable area will contract, requiring a shift from arable farming to cattle ranching.

West Africa and northeast Africa: a northward shift of the ITCZ, which is implied by GHG warming, is expected to increase summer precipitation (Working Group I Report).

However, evaporation also increases, so that there are both increases and decreases of crop-water availability over the region, and it is at present uncertain how these differences will be geographically distributed. Where precipitation exceeds évapotranspiration this could reduce current constraints on agriculture by increasing crop-water availability. It could also be expected, however, to encourage the northward extension of locusts and other pests (Boko, 1988).

Where increases in precipitation were insufficient to compensate for increases in évapotranspiration under high temperatures, this would reduce crop-water availability. Although no specific impact assessments have yet been completed for this region, studies of analogous individual dry years in Benin and Nigeria such as those of 1973 and 1978, imply substantial reductions in agricultural output (Boko, 1988; Oguntoyinbo, personal communication, 1989).

Any decreases in rainfall or its concentration into a shorter rainy period could reduce yields of maize and the carrying capacity of rangeland for cattle. Erosion and flooding could become more troublesome in mountain regions such as in Ethiopia (Haile, 1989)

East Africa and southern Africa: estimated increases in temperature for an equivalent doubling of atmospheric CO_2 are around 1.5°C to 3.5°C for this region, depending on latitude. This would lead to rates of évapotranspiration being increased by ca 5%

to 15% (Schulze, personal communication, 1989). Much depends on changes in precipitation, which would profoundly affect maize yields and grass growth (and thus carrying capacity) of rangelands. In Kenya, the driest 10% of years occurring at present lead to reductions of maize yield by ca 30% to 70% and of forage yield by 15-60% (Akong'a et al., 1988). Any changes in the frequency of such years would clearly substantially affect the average output of agriculture in the region. Improved knowledge of possible GHG-induced changes in the probability distribution of rainfall in this and other semi-arid regions is thus a matter demanding a high priority in future research.

Asia

China: there are indications that global warming would lead to a weaker winter but stronger summer monsoon. Rainfall receipt could thus increase in already rainy areas, and would extend further westward and northward than at present. If this were to occur then the risk of flooding in southern China, which is already serious in wet years, might be significantly increased. Under a 1°C warming and with precipitation increases of 100 mm yields of rice, maize and wheat are estimated to increase by about 10% overall nationally, though there may be modest decreases in the north and east (Zhang, 1989).

Without increases in available moisture, however, maize yields in the eastern and central regions decrease on average by 3% per 1°C increase (Terjung et al., 1984).

India: in Northern India a temperature increase of 0.5°C is estimated to reduce wheat yields by about 10% (Sinha, personal communication, 1989). Similar increases in central India would probably lead to larger percentage reductions from a lower base yield. However, given sufficient increases in rainfall, rice yields may increase perhaps ca 7% with +2.5°C and +0.75 mm rainfall per day (Van Diepen et al., 1987). The fertilising effect of CO_2 could enhance this increase to over 20%. Sorghum yields in central southern India are estimated to decrease in response to higher temperatures during the rainy season, owing to premature development and reduced grain filling (Jodha et al., 1988). During the post rainy season, however, when moisture is currently in short supply, increases in temperatures may lead to increases in yield because the period of moisture stress would be reduced by a shortened growing period.

SE Asia: intensification of the SE Asia monsoon would tend to lead to increased summer but reduced winter rainfall. Preliminary indications are that with rainfall changes of +5% (summer) and -11.4% (winter) (which equate to a GISS 2 x CO_2 climate), irrigation requirements in northern Thailand would decrease by ca 3% in summer and increase by ca 30% in winter (Panturat and Eddy, 1989). Resulting potential rice yields would decrease by 1-7%, although the direct CO_2 effect could enable increases of 4-13%. Increases in temperature expected under an equilibrium 2 x CO_2 climate are +0.3° to +0.5°, which could lead to reduced rice and maize yields (due to more rapid crop growth) and to an increase in losses to pests (Nguyen Huu Ninh, personal communication, 1989). Experiments in the Philippines indicate that increased summer rainfall, with small increases in temperature combined with the effect of elevated CO_2 could raise rice yields by up to 30% (Van Diepen et al., 1987).

Japan: under a warming of 3°-3.5°C and a 5% increase in annual precipitation (the GISS 2 x CO_2 climate), rice yields are expected to increase in the north (Hokkaido) by ca 5%, and in the north-central region (Tohoku) by ca 2%, if appropriate technological adjustments are made (Yoshino et al., 1988). The average increase for the country overall is ca 2-5%. Cultivation limits for rice would rise about 500 m and advance ca 100 km north in Hokkaido. Yields of maize and soybeans are both estimated to increase by about 4%. Sugarcane yields in the most southern part of Japan could decrease if rainfall was reduced. The northern economic limit of citrus fruits would shift from southern Japan to northern Honshu Island (Yoshino, personal communication, 1989). Net primary productivity of natural vegetation is expected to increase by ca 15% in the north, ca 7% in the centre and south of Japan (Yoshino et al., 1988).

Oceania

New Zealand: grassland production is estimated to increase by 6%, 9% and 18% under a 1°, 2° and 3°C warming. There may be a decrease in the area under wheat, barley and oats and an increase in the area under maize and vegetables (though a decrease of the latter in North Island - Salinger et al., 1989b). Maize yields would increase, as would those of potatoes and other vegetables (except in North Island). The area under pipfruit would shift further southwards in South Island; berry fruit would shift south to South Island. Kiwi fruit yields may increase 15-20%, but the major growing areas may also shift south, as would viticulture.

Australia: there are indications that GHG forcing will lead to increases in summer rainfall where there is at present a summer rainfall maximum, and more uncertainly to decreases in winter rainfall where there is at present a winter rainfall maximum (Pittock, 1989). Under a 40% increase in summer rainfall and 20% decrease in winter rainfall, and with increases in mean annual temperature of 1°C at 10°S, 2°C at 20°S, 3°C at 30°S and 4°C at 40°S, net primary productivity increases by about 30% at 10-20°S, 25% at 20-30°S and 10-15% at 30-40°S (Pittock and Nix, 1986). There would be increases in wheat yields in the eastern wheatbelt, but a decrease in Western Australia (Pittock, personal communication, 1989). Present marginal areas of wheat production, particularly in southwestern Western Australia, northwestern Victoria and western South Australia could decrease. Experimental work suggests that spring wheat yields could increase by about 20% and 27% under a 2°C and 3°C warming respectively, provided there was sufficient water for full irrigation. Dryland wheat yields would decrease unless there occurred a substantial increase in rainfall (Gifford, 1988). The area under maize and sorghum may increase at the expense of wheat, barley and oats, particularly in northern New South Wales. There would be an increase in yields of sugarcane and tropical fruits, with a tendency for a southward shift of these from Queensland into northern New South Wales (Pittock, personal communication, 1989; Linforth, personal communication, 1989). However, yields of temperate fruits (apples, pears etc) would decline and areas of production would be pushed into southern Victoria and Tasmania (Pittock, personal communication, 1989). Increased grass growth would allow greater cattle production, but problems of heat stress in sheep would increase. Cattle might therefore increase their range at the expense of sheep (Pittock, personal communication, 1989). Potential benefits from increased grass growth will unfortunately more than likely be offset by the poor nutritive value of tropical as compared with temperate species. This, together with (a) loss of the Mediterranean-type climatic zones of Victoria and Western Australia, which are the prime lamb and wool producing areas, and (b) increased heat stress of both sheep and cattle, means that livestock productivity will very probably decrease.

Pacific Islands: the most important impacts on agriculture in this region stem from rises in sea-level. In Fiji, for example, islands such as Moala and Vatulele would lose 8.8% and 6.2% respectively of the land area with a 1.5 m rise in sea-level (though this is not currently estimated to occur before 2100). As a consequence, there could be a decrease in the productive potential for subsistence crops, such as yams, and for commercial crops, particularly those such as copra for which production is concentrated on the coastal fringe (Nunn, 1988; New Zealand Intelligence Assessments Committee, 1988). Any increases in frequency of tropical storms could have a detrimental effect on copra production.

vi) Higher order effects on economy and society

The various effects that climatic changes could have on crop yields and the carrying capacity of grassland can, through a web of reinforcing and countervailing circumstances, have a number of higher order effects on (for example) farm incomes, rural employment, national food production, national food security and exports. The latter, in turn, may influence the pattern of international food trade and food prices. This section summarises the range of possible higher order effects and illustrates these by reference to results from recent impact assessments. It does not purport to be a comprehensive statement of such effects, which are bound to be specific to the local economic and political environment, to the technical and management characteristics of particular farming types, and to the rates and magnitudes of climatic change - all of which will vary from region to region. Moreover, the few studies thus far completed are limited to the developed countries and it is important to emphasise that the magnitude of these higher order effects will depend greatly on the technical adjustments and policy responses to climatic changes. The data presented below are therefore simply illustrative of the type of possible effects rather than of their specific nature.

Effects on production costs Some changes in costs of inputs can be expected to flow directly from altered management requirements. In the US, for example, irrigation requirements have been estimated to increase by 20-25% in the southern Great Plains and Corn Belt under a warming of 4.5°C and with precipitation reduced by about 12.5% (95 mm), at a time when groundwater depiction is likely to accelerate as a result of reduced recharge rates from snowmelt in the Rocky Mts (EPA, 1989). The costs of operations to reduce pest damage may also alter (EPA,1989).

In centrally planned economies, where production targets tend to be fixed and where inputs are often adjusted to counter climate-related variations of yield, it is possible to estimate the extent to which production costs may alter in relation to altered yield potential. In the Central (Moscow) Region of the USSR, for example, a 1°C temperature increase may reduce production costs of winter wheat and corn by 22% and 6%, respectively, while increasing production costs of cool-summer crops such as barley, oats and potatoes (Parry and Carter, 1988; Pitovranov et al., 1988a).

Other, possibly more significant, cost increases may derive from changes in prices of agricultural inputs due to changes in government policy, particularly those policies that may be designed to mitigate the greenhouse effect (for instance, by increasing energy and fertiliser prices). These indirect effects are considered in Working Group III Report.

Effects on net returns, profitability and farm incomes These will depend, among other things, on changes in costs of inputs and the prices of outputs (and no adequate estimation of these is currently feasible). Recent regional impact assessments have considered price responses only within a national, rather than international, context (cf EPA, 1989).

Assuming, unrealistically, that prices and input costs remain constant, then changes in farm profitability and incomes are estimated to alter in sympathy with changes in yield potential. To illustrate, in Saskatchewan (Canada) where spring wheat yields are estimated to decrease by 18% under a warming of 3°-4°C with reduced soil moisture and where yields of other cereals and oilseed are assumed to decline by the same proportion, farm incomes are projected to decline by 7% and farm expenditures on goods from other sectors by ca 0.5% (Williams et al., 1988). In contrast, in southern Finland, increased yield potential is estimated to raise net returns to barley cultivation by about three-quarters (Kettunen et al., 1988). It should be emphasised, however, that these assessments take no account of changes in the worldwide supply, demand and price of agricultural products.

Effects on rural employment, society and settlement Very little attention has been given to these, and such current estimates as exist are based on present-day statistical relationships with farm income, which are likely to change in the future. For example, in Saskatchewan, the reduced farm incomes described above are projected to lead to reductions of 0.8% and 0.5% in agricultural and provincial employment respectively (Williams et al., 1988).

Effects on regional and national production These are strongly dependent on the many adjustments in agricultural technology and management that undoubtedly will occur in response to any climate change. So numerous and varied are these adjustments likely to be, however, that it is extraordinarily difficult to evaluate their ultimate effect on aggregate production. In this part of the report we consider the effects on production that are likely to stem directly from changes in yield, unmodified by altered technology and management. Adjustments in technology and management will be discussed later (Section 2.7). Unless otherwise stated the following estimates are for impacts under GCM 2 x CO_2 scenarios of altered climate.

The large regional differences in estimated altered production in the US typifies the complexity of the issue: the largest reductions under a range of possible 2 x CO_2 climates are projected for sorghum (-20%), maize (-13%) and rice (-11%) (EPA, 1989). Overall, production is estimated to be sufficient for domestic needs, but the potential for export is reduced. In Canada, production is estimated to decrease in Alberta and Saskatchewan, but perhaps increase in Manitoba and Ontario (Smit, 1987; Arthur, 1988). In northern Europe cereal production might increase in the order of 15%, and livestock production would be greater as a result of the higher carrying capacities of pasture (Bergthorsson et al., 1988, Kettunen et al., 1988; Koster et al., 1987). In Western Europe, production may increase in the Low Countries, UK and Denmark (if available moisture levels are maintained), but decrease in France and FRG (if there is reduced available moisture resulting from higher temperatures) (Santer, 1985; Parry et al., 1989). In the Mediterranean region production may fall substantially if GCM projections of reduced rainfall prove to be correct (Santer, 1985). There is currently no agreement between GCMs as to how moisture levels may change in eastern Europe, but reductions in moisture would tend to reduce production (Farago, personal communication, 1989; Parry et al., 1987). In the USSR warming would enable production to be increased near the present northern limit of commercial winter wheat cultivation. Further south, in the current major producing regions of Ukraine and Kazakhstan, increases in moisture (which are most uncertain) would also enable output of winter wheat and maize to be increased (Pitovranov et al., 1988b; Nikonov et al., 1988; Mendhzulin, personal communication, 1989; Sirotenko, personal communication, 1989).

Our limited knowledge of the implications of climate change for overall production, together with great uncertainties about future regional patterns of comparative advantage, make hazardous any assessment concerning effects on patterns and quantities of exports. A few estimates have, however, been made. Exports of some crops in the US are projected to decline by up to 70% under the most adverse climatic changes simulated for a doubling of GHG (EPA, 1989). Exports of maize and wheat may increase for Canada, but decrease for barley (Land Evaluation Group, 1987). Sweden and Finland could probably export more cereals (Koster et al., 1987), as could Denmark, the Low Countries, UK and FRG (Santer, 1985). However, the countries around the Mediterranean might experience reduced possibilities for export as a result of reduced productive potential (Santer, 1985).

Implications for food supply and food security In high mid-latitude countries, where warming tends to reduce climatic constraints on agriculture, increases in productive potential would, if current price and policy incentives continue, be likely to lead to increases in surplus production.

In regions where productive potential is reduced, which is possible in the low mid latitudes and low latitudes as a result of decreased water availability, there could occur a reduction of levels of food security. The most vulnerable regions are probably Africa and South America. Smaller nations are likely to be affected more than large ones because of the smaller opportunity for risk pooling across climatic regions (Sinha et al., 1988). Overall, there is no compelling evidence that global food supplies will be radically diminished (Crosson, 1989), but of greater concern is the possibility that inherently vulnerable regions may have their already limited productive capacity further reduced by warming and drying. This is considered in greater detail in Section 2.4 of this report.

Effects on prices and trade Since the effects of changes in climate will occur on a global agricultural system that is, itself, constantly changing and since possible climate-induced changes in production in one region will almost certainly affect changes elsewhere.

At present it is merely possible to consider, in a very simple manner, the effect that future climatic change would have on present-day agriculture, if it were to occur *now* under present technology, management and trade structures. The following is a preliminary analysis based on estimates of generalised climate-induced changes in production, inferred from the changes in productive potential outlined above (Section 2.6.3 above).

It should be emphasised that these estimates do not, for two reasons, represent a forecast of impacts. First, they do not take into account the spontaneous adjustments that will occur within agriculture and which will markedly affect how production responds to climate change. Second, they are based on a most imperfect understanding of those changes in climate that may occur and of their effect on crop yields, soils, pests, diseases etc (Smit, 1989).

Under the estimate of changes in productive potential outlined in this report, prices of some mid-latitude crops such as maize and soybean could increase in the order of 10%, reflecting a small net decrease in the food production capability of the world. Rice production could, however, increase if available moisture increased in Southeast Asia. The average global increase in production costs due to climate could thus be small (perhaps a few per cent of world agricultural GDP). This accords with estimates that, worldwide, average agricultural production could increase by 10-20% (Schelling, 1983), result of the greenhouse effect.

Much depends, however, on how beneficial are the effects of increased CO_2 on crop yield. If productivity is substantially enhanced *and* more moisture is available in some major production areas, then world production of staple cereals could increase relative to demand with food prices reduced as a result. If, on the contrary, there is little beneficial direct CO_2 effect *and* climate changes are negative for agricultural potential in all or most of the major food-exporting areas, then the average costs of world agricultural production could increase significantly. These decreases or increases in production potential could result in decreases or increases in costs equivalent to perhaps over 10% of the value of world agriculture. It should be emphasised, however, that even larger changes in costs are likely to stem from non-climatic factors such as population, income and technology.

These estimations of the average effect of world production do not include the short-term impacts that might occur as a result of the increased risk of a concurrent downturn of production due to global warming. If, for example, higher temperatures and évapotranspiration rates led to a single concurrent drought in the major producing regions, the implications for world prices in the short term could be substantial. Figure 2.1 illustrates the change in commodity prices that could occur as a result of concurrent yield reductions of between 10% and 50% in the US, European Community and Canada. Assuming there were no other climatic effects on production elsewhere, agricultural prices would increase by about 10%, and by a third for a 50% fall. If there were concurrent yield decreases of 25% in Africa and Southeast Asia, agricultural prices would increase by a fifth and a half respectively (Kane et al, 1989).

While it is certain that regional agricultural changes will result from climatic change, it remains highly uncertain which specific region will actually experience yield gains or losses because (i) regional climate scenarios remain imprecise, (ii) capability of farmers to respond to climate change remains uncertain and may vary across regions and (iii) the tolerance of crops to the range of climate conditions under altered climate have not been fully assessed. Agricultural trade will play a significant role in determining the direction of regional impact because changing world agricultural prices will present opportunities and costs for producers and consumers of agricultural products. Thus, a nation's farm sector may benefit from improved yields and higher commodity prices while its population may be adversely affected by higher prices for food. These changes would be reversed if the world generally benefits from climate change and world commodity prices fall.

2.7 Likely adjustments in agriculture

2.7.1 Introduction

The foregoing analyses have assumed that technology and management in agriculture do not alter significantly in response to climate change, and thus do not alter the magnitude and nature of the impacts that may stem from that change. It is certain, however, that agriculture will adjust and although these adjustments will be constrained by economic and political factors, it is likely that they will have an important bearing on future impacts.

There are two broad types of adjustment that may occur. Those at the farm level that flow from decisions as a result of farmers' perception of altered conditions; and those at the regional, national and international levels that flow from changes in government policy. This report considers only those farm-level adjustments that are likely to occur in an intuitive and spontaneous manner as a result of perceived changes of climate, and do not require explicit changes in government policy. Consideration of the latter falls within the responsibilities of Working Group III.

Because of the very wide array of potential adjustments, which will vary according to type of climate change, type of farming, and many other factors, it is not profitable (even if sufficient information on likely changes of climate were available) to generalise at length about them. More specific discussion is needed at the regional case study level than is appropriate here. In this report we simply list and illustrate the various types of adjustment and their likely efficacy under different types of climate change.

Three broad types of adjustment may be expected: changes in land use, management and infrastructure.

2.7.2 Changes in land use

Three types of land use change may be considered: changes in farmed area, crop type and crop location.

i) Changes in farmed area

Where warming tends to reduce climatic constraints on agriculture, such as in high latitude and high altitude areas, an extension of the farmed area can be expected if other environmental factors and economic incentives permit. Expansion may be most marked in the USSR and northwest and northern Europe, where terrain and soils would permit further reclamation (Pitovranov et al., 1988a; Squire and Unsworth, 1988). It may be limited in much of Canada, with the exception of the Peace River region in northern Alberta and parts of Ontario (Arthur, 1988; Smit, 1987). There may also be potential for high latitude reclamation in some of the valleys of central Alaska, in northern Japan and in southern Argentina and New Zealand (Jager, 1988; Salinger et al., 1989).

Warming may also tend to induce an upward extension of the farmed area in upland regions. As indicated in Section 2.6.3 (above) a 1°C warming in the European Alps can be expected to raise climatic limits to cultivation by ca 150 m. Similar upward shifts are estimated to increase the farmed area significantly in high mid latitude mountain environments such as northern Japan and South Island New Zealand (Yoshino et al.,1988; Salinger et al.,1989). These shifts of the limit of the farmed area imply major impacts on the semi-natural environment and on extensive rangeland economies in mountain regions, such as Alpine pastures, which may come under pressure both from the upward advance of more intensive agriculture and from afforestation (Balteanu et al., 1987).

In regions where reduced moisture availability leads to decreased productive potential, particularly where current agriculture is only marginally productive, there may occur a significant decline in acreage under use. This may occur, for example, in parts of the eastern Mediterranean if projected decreases in rainfall are correct, and also possibly in western Australia (Santer, 1985; Pittock, personal communication, 1989). In the southeast US, increased heat stress and evaporation losses may reduce profitability to the point where commercial cropping becomes non-viable. For example, the cropped acreage in the southern Great Plains of the US is estimated to decline by between 5% and 23% under a warmer and drier 2 x CO_2 climate, but is partially compensated by increases in cultivated area in the Great Lakes region (EPA, 1989).

ii) Changes in crop type

Changes to crops with higher thermal requirements In regions where there are substantial increases in the warmth of the growing season (and where output is currently limited by temperature rather than by rainfall) it is logical that substitution by crops with higher thermal requirements, that would make fuller use of the extended and more intense growing season, should allow higher yields. Recent impact assessments have considered this as a predictable response in the US, UK, Japan and New Zealand (EPA, 1989; Rowntree et al., 1989; Yoshino et al., 1988; Salinger et al., 1989). To illustrate, yields of present-day quick-maturing rice varieties in northern Japan would probably increase by about 4% with the 35% increase in growing degree-days estimated under the GISS 2 x CO_2 scenario (Yoshino et al., 1988). However, the adoption of late-maturing rice (at present grown in central Japan) might increase yields by 26%.

Changes in annual crops can be made relatively swiftly, but a switch in perennials (such as from temperate to citrus tree crops) will require more time.

Change to more drought tolerant crops Where moisture rather than temperature is more generally the current climatic constraint on output, or where increases in temperature could well lead to higher rates of évapotranspiration and thus to reduced levels of available moisture, there may occur a switch to crops with lower moisture requirements. Once again the lack of information on likely changes in rainfall makes further speculation on this unprofitable, particularly at lower latitudes. However, there is some evidence that, at high mid-latitudes, a switch from spring to winter varieties of cereals would be one strategy for avoiding losses in more frequent dry spells in the early summer. This might be the case in Scandinavia and on the Canadian Prairies (Koster et al., 1987; Williams et al., 1988).

Hi) Changes in crop location

The switch of crops considered above implies changes in the allocation of land to given uses. In general, land uses which show a greater productivity per unit area than others are likely to increase their comparative advantage over competing uses; and given sufficient change in the pattern of comparative advantage, then decisions may follow which involve a change in use. The amount of land use change is likely to depend on how finely land uses in a given area are currently tuned to economics and climate, and much will depend on the changes in price that are largely determined by changes in potential in other areas. The response is therefore likely to be complex and extremely difficult to predict. As a much simplified illustration, consider the effect that a 1°C warming may have on land use in the area around Moscow, USSR. Yields of winter wheat and silage maize may increase because they are currently limited by temperature, but yields of temperate-zone crops such as barley and oats are reduced. Experiments suggest that the optimal reallocation of land under these circumstances would be a 30% and 5% increase in land under winter wheat and maize, and a 20-30% decrease in land under barley and oats (Parry and Carter, 1988; Pitovranov et al., 1988a).

The broad-scale changes in crop location imply a general poleward shift of present day agricultural zones. This is likely to be most pronounced in mid- and high- latitudes, partly because warming will be most marked here, but largely because it is in these regions that latitudinal zoning is most evident as a result of differences in available warmth for crop maturation.

In the UK, northern limits of sunflower production, which are at present located in the extreme south of the country, would shift about 300 km northwards for each degree ca rise in mean annual temperature (Parry et al., 1989). Broadly similar shifts are projected for southern Scandinavia where maize, soybeans, oilseeds and a wider range of fruits and vegetables would be viable (Koster et al., 1987). In southern Europe, higher temperatures imply a more northerly location of present limits of citrus, olives and vines (Imeson et al., 1987).

In central North America zones of farming types are estimated to shift ca 175 km northwards for each °C of warming, resulting in reduced intensity of use in the south, and increased intensity in the north where soils and terrain permit (EPA, 1989). In Canada up to 4m ha of currently unused northern soils may be suitable for cultivation in a warmer climate (Smit et al., 1989) A northward movement of production would suggest that a sizeable area of output currently located in the northern Great Plains of the US would relocate in the southern Canadian Prairies.

Similar southward shifts of land use have been suggested for the Southern Hemisphere, perhaps up to 6° of latitude (670 km) under a 2 x CO_2 climate (Salinger et al., 1989). It should be emphasised, however, that these broad-scale effects will be much affected at local levels by regional variations in soils etc, by the competitiveness of different crops and their environmental requirements and, most importantly, by regional patterns of rainfall, none of which can adequately be projected at the present.

2.7.3 Changes in management

It is reasonable to expect that a large number of changes in management, adopted over time as the effects of climate change are perceived, will modify these effects outlined above. As a unit exposed to impact, agriculture is thus a moving target, continually adjusting itself both to perceived non-climatic and climatic conditions. The following summary covers only those adjustments that are likely to occur without the stimulus of change in national or international government policy on agriculture. The latter are considered in Working Group III Report.

i) Changes in irrigation

There are likely to occur very substantial increases in the need for and the costs of irrigation, in order to substitute for moisture losses due to increased evapotranspiration. The most detailed estimates yet available are for the US, where irrigation requirements may increase by about 25% in the southern and 10% in the northern Great Plains under a 2 x CO_2 climate. Given the likely increased rate of groundwater depletion, this will probably lead to significantly higher costs of production, with consequent shifts to less water-demanding uses in the most affected areas (EPA, 1989).

Substantially increased irrigation needs are also projected for most of western and southern Europe (Imeson et al., 1987). Elsewhere, although data are not available, it is probable that effects will be similar where available water is reduced. Where there are substantial rainfall increases changes in management may be needed to tackle soil erosion, etc (see below).

Irrigation is practised mostly in arid or semi-arid regions where there is already a strain on available resources. Most of the irrigated land of the world is in Asia with a rapidly increasing population and not much latitude for increases in use of land and water resources. To counter the increased water demand due to climate change, tighter water management practices should lead to higher irrigation efficiency.

ii) Changes in fertiliser use

More use of fertilisers may be needed to maintain soil fertility where increases in leaching stem from increased rainfall, such as in New Zealand (Salinger et al., 1989). In other regions, warming may increase productive potential to the extent that current levels of output can be achieved with substantially lower amounts of fertilisers. In Iceland, for example, fertiliser use could possibly be halved under a 2 x CO_2 climate while maintaining present day output (Bergthorsson et al., 1988).

Much will depend on other factors, for example how far higher CO_2 will make nutrients more limiting, thus requiring more use of fertilisers, and how future changes in energy prices affect the cost of fertilisers.

iii) Control of pests and diseases

The costs of these are likely to alter substantially, although it is quite impossible to specify them with any degree of detail. Possibly most important for global cereal production may be the costs of controlling the spread of subtropical weed species into the current major cereal-producing regions (EPA, 1989).

iv) Soil drainage and the control of erosion

Adjustments in management are likely to be necessary in tropical regions, particularly those characterised by monsoon rainfall, where there is an overall increase, or at least increase in the intensity of rainfall. Recent assessments in the USSR have indicated that, over the longer term, reduced soil fertility, increased salinity and the costs of erosion control may more than offset the beneficial effects of a warmer climate, leading ultimately to reduced yields and higher production costs (Pitovranov et al., 1988a).

v) Changes in farm infrastructure

Regional shifts of farming types and altered irrigation requirements imply major changes in types of capital equipment, in farm layout and in agricultural support services (marketing, credit etc). In the US it has been estimated that these will be substantial (EPA, 1989). Because of the very large costs involved only small, incremental adjustments may occur without changes in government policies.

vi) Changes in crop and livestock husbandry

The adjustments summarised above imply a plethora of small, but important changes in farm husbandry. In particular there are likely to occur very many alterations to the timing of various farm operations such as of tillage (ploughing, sowing, harvesting etc), of fertilising and of pest and weed control (spraying etc), because the timing of these in the present farming calendar, though of course different for various parts of the world, is frequently affected by present climate. Particular aspects of husbandry are also likely to be affected, such as the density of planting, the use of fallowing and mulching and the extent of inter-cropping. These aspects are, today, frequently part of a package of strategies designed to mitigate the adverse effects (and exploit the beneficial effects) of present-day climate. Thus a change of climate implies a retuning of these strategies to harmonise with the new set of climatic conditions.

An illustration of this is the management of double cropping (of summer rice and winter barley) in Japan. At present the northern limit of double cropping is located at 37°N. Under the increased temperatures projected for an equivalent doubling of CO_2, double cropping would be viable 150 km further north, though, the response to this northward shift of potential would depend greatly on crop prices and input costs (Yoshino, personal communication, 1989).

An indication of the impact on animal production systems is given by preliminary work in Ireland. Here livestock production is currently dominated by the effects of high rainfall and wet soils (Brereton, 1989). A high proportion of grassland in Ireland is affected by high water tables. Total feed production might not be greatly affected but the low-cost grazing system would not be sustainable and there would be a shift to indoor feeding systems, with a consequent increase in the problem of waste disposal (Keane, personal communication, 1990).

2.7.4 Changes in policies of agricultural support

In most countries agriculture is currently affected in many different ways by a wide range of government policies that influences product prices, costs of farm inputs, marketing arrangements, the cost of credit and even the levels of production of specific commodities. Relatively minor alterations to these policies can have a marked and quite rapid effect on agriculture. In large countries, and in supranational organisations such as the European Community, a few decisions of policy can affect production over large areas. It is likely, then, that changes in government policy resulting from changes in climate would have a marked influence on how agriculture ultimately responds. These issues are discussed in Working Group III Report.

2.8 Effects of changes in sea-level

2.8.1 Scenarios

Sea-level change Global warming as a result of increased concentrations of GHG is likely to cause an acceleration of the slow sea-level rise already in progress. This expected acceleration will be the consequence of thermal expansion of oceanic surface layers and melting of glaciers and polar icecaps.

It is generally accepted that global sea-level has risen by 10-15 cm over the last century but it is not certain if this is entirely attributable to the greenhouse effect. Current estimates suggest a further rise of 10-30 cm by 2030 (Working Group I).

2.8.2 Vulnerability

Vulnerability studies frequently take an assumed sea-level rise as the major, and often only, factor. Impacts are assessed usually in terms of vulnerability to inundation and its probable consequences for land management and agriculture. Coastal regions of low elevation can be identified by reference to contoured maps and remote sensing sources. However, contour information is inadequate worldwide and remote sensing insufficiently accurate. Therefore to date a coastal lowland morphological categorisation has been used for broad global investigations (UNEP, 1989). Categories of high vulnerability include deltas, polders, areas subject to marine flood damage, areas with certain soil types (eg young fluviosols, gleysols), small islands and atolls, and wetlands including mangrove swamps and marshes (UNEP, 1989).

2.8.3 Vulnerable regions

The draft ISOS (Impact of Sea Level Rise on Society) Report (UNEP, 1989) provides a global inventory of high risk areas using information on terrestrial topography as the key determinant. Areas with more than 100 persons per km^2 were given priority consideration. Most countries in the world are vulnerable to some extent since fewer than 30 are entirely landlocked. Over 50 million people could be forced to relocate with the scale of sea-level change considered (+1.5 m). Inundation of important agricultural lands supporting such a population is implied unless protective measures are implemented. A master checklist of 27 vulnerable countries was compiled, omitting developed nations regarded capable of protective action. The 27 nations can be grouped regionally, scores indicating an ascending scale of vulnerability (1 to 10) based on the votes of experts who were asked to select what they considered to be the ten most vulnerable countries to sea-level rise. Four countries/ regions received no votes for the ten most vulnerable list, although they are still identified as being among the 27 most likely to experience serious impacts. The groups and scores are:

Asia Bangladesh (10), Burma (1), China (8), India (2), Indonesia (4), Malaysia (-), Pakistan (2), Philippines (2), Sri Lanka (1), Taiwan (1), Thailand (9), Vietnam (2)

South America Argentina (4), Brazil (7), Colombia (-), Ecuador (-), Surinam (1), Venezuela (2)

Africa Egypt (9), Kenya (1), Mozambique (2), Nigeria (2), Senegal (2), The Gambia (1)

Islands Caribbean (-), Maldives (1), Pacific Islands (1)

To these may be added major regions in developed countries:

Europe Southern North Sea coasts (eastern England, northern Belgium, Netherlands, northern Germany (FDR), western Denmark (7); eastern North Italian Plain (3); head of Gulf of Finland (mainly USSR) (1); western Black Sea coasts of USSR (1)
Asia Japan (Pacific coastlands of Honshu) (1)
North America Gulf Coast of Mexico (1), Louisiana (6), Florida and US East Coast States (1)

2.8.4 Direct impacts on agriculture

Direct impacts refer to the effects of inundation. Agricultural lands could be flooded permanently, some lost by increased marine erosion and some frequently inundated as a result of disrupted river and tidal regimes together with greater storm and high wave incidence. The nature of acceleration of sea-level change is crucial because many environments have so far kept pace with the slow rise (eg through coral, silt or peat accretion) but may not be able to do so in the near future.

The most significant impacts can be summarised by reference to the 27 countries designated vulnerable (2.8.3 above):

Asia Southeast Asia would be seriously affected because of the extreme vulnerability of several large deltaic regions with dense populations supported by paddy rice cultivation. For example Bangladesh would have 15% of land inundated with a 1.5 m rise, with another 6% below 3 m made vulnerable. Altogether 21.3% of agricultural production could be lost, mainly rice, sugarcane and jute (UNEP, 1989). Thailand and China are regarded as also being especially vulnerable to large farmland losses.

South America Losses through inundation would occur in the districts of the Pampas of Argentina bordering the Plate estuary with consequent reduced cereal (wheat/maize) and cattle production. Some sections of the Brazilian coastlands and the Amazon delta are vulnerable with losses of tropical agriculture (sugarcane, citrus fruits, oilpalm, cocoa etc). Coastal regions of Venezuela and Surinam would lose rice, banana and sugarcane lands.

Africa Assuming a 1.5 m sea-level rise, most losses would be in the large delta areas of The Gambia, Senegal, Nigeria, Mozambique and Egypt. Of these the Nile Delta/lower Nile Valley in Egypt is the most intensively cultivated so that 17% of national agricultural production and 20% of farmland could be lost with severe impacts on food supplies (especially of rice, wheat, vegetables) and non-food crops (eg cotton).

Islands Many coral atolls and small islands have very limited relief above present sea-level and so could have the greatest proportional losses of farmland in the world. As an example of an atoll group, the Maldive Islands in the Indian Ocean would have 50% of all land inundated with a 2 m rise (Delft Hydraulics Lab, 1986). An additional danger is that sea defences might not be effective owing to coral porosity and underground seawater flow. Even islands with higher terrain, such as Fiji, would lose much of their farmland, Vatulele losing 6.2% of agricultural land with a 1.5 m rise and 31% with a 3.5 m change. Moala would lose 8.8% and 15% of farmland respectively (Nunn, 1988).

Developed countries Not all developed countries have the resources for works to counteract inundation especially where rapid sea-level rises occur in regions of coastal downwarping. For example a i m downwarping has occurred over the last hundred years in the Mississippi Delta region of the US. Land is being lost here at a rate of 250 km^2 per year and 35% of the estimated national dryland loss from a 0.5 m sea-level rise would be in Louisiana (EPA., 1989). Consequent loss of subtropical agriculture in the US would be considerable.

The north and west of The Netherlands is reclaimed polder land with protective dykes and artificial drainage, representing some of the most intensively farmed land in the world. Defences constructed after the serious inundation of 1953 are designed to withstand a 10,000 year surge event, but even here a 1 m sea-level change would reduce that safety margin by an order of magnitude (Hekstra, 1986). The southern North Sea coastlands are also subject to crustal downwarping that would exaggerate any change.

2.8.5 Indirect impacts on agriculture

In many coastal regions indirect or secondary impacts of rising sea-level may have far-reaching significance for agriculture. Costs of protection of vulnerable farmland would escalate. In addition to improvement of coastal defences, the higher level of rivers approaching the sea would necessitate adjustment of dykes, sluices and pumping systems. This is especially so where the general land level is no longer rising because flood protection schemes prevent any further silt accumulation. In developed nations decisions have to be made concerning expenditure for protection of relatively low-value farmlands compared with urban land. Measures may be more essential for subsistence agriculture in a developing country. Modifications of land drainage systems would require further resources where they need to be adapted to rivers with higher levels and inhibited outflow.

Saltwater intrusion into surface water and groundwater could have deleterious effects. Deeper tidal penetration could increase the danger of flooding causing salinisation of farmlands and reducing the value of river water for irrigation. Aquifers could be recharged with sea water if abstraction occurs to below sea-level. Rising sea-levels could raise underground saltwater levels to reduce the depth of overlying fresh groundwater. In areas of low relief, such as atolls, freshwater reservoirs of less than 1 m depth could disappear in dry seasons, as water tables fall to saltwater levels, leaving no useful irrigation supply.

Threats of inundation could lead to relocation of farming and farming employment. If this is feasible there are obvious implications for land acquisition, land preparation, infrastructural changes and farming modifications. But relocations could be prohibitively large scale as in Bangladesh where some 20% of farmland and population could be affected by a 1 m sea-level rise (UNEP, 1989). Often relocation could be difficult as in Egypt where irrigation is feasible in the delta and flood plain areas only. Sometimes, relocation would be impossible, as in the Maldives where half the land would be lost as a result of a 1 m sea-level rise and the remaining half would he within a vulnerable 1 m of sea-level (Delft Hydraulic Lab, 1986). Out-migration of population would be the only solution for many small oceanic islands.

3 Potential impacts on managed forests and the forest sector

3.1 Introduction

The social, economic and environmental aspects of major forest ecosystems are significant, but often neglected, attributes of forest policies (Shea and Carlson, 1984). Forests and woodland cover roughly one-third of the land surface of the world, and therefore deserve serious consideration in assessments of socioeconomic implications of climatic changes. Monitoring, evaluation and feedback concerning the social, economic and environmental aspects of forestry need to be accounted for in planning forest-related programs. A comprehensive international effort is necessary to assess objectively the socioeconomic impacts, given the variety of languages, customs, social and political systems. International bodies such as FAO, WMO, UNEP, IUFRO and IUCN are examples of basic structures used to foster these global assessments. The prediction of changes and consequences fifty years or more into the future, with large elements of risk and uncertainty, is a challenging and necessary effort. The need to develop proactive, not reactive, strategies will be one of forestry's greatest challenges.

3.2 Managed and unmanaged forests

Although the distinction between 'unmanaged' and 'managed' forests is seldom clear (Warrick et al., 1986), this report considers managed forests to have some degree of planned or actual physical intervention and include the following levels of intervention:

- Extensive silviculture with attention to harvest design to promote natural regeneration, and subsequent protection.

- Basic silviculture with plantations established after harvesting, followed by more intensive protection.

- Intensive management with multiple inputs, including site preparation, planting, competition control, pre-commercial or commercial thinning and protection from insects and fire.

- Elite management regimes dedicated to short rotations using many of the above methods plus fertilisers to promote growth.

It is particularly difficult to determine how much of the world's forests are under each level of management. Therefore, this report incorporates all forests in which some harvest takes place, with particular emphasis on forests where there is some degree of management. The definition excludes protected forests, forest parks and wilderness areas.

In many forests around the world, stands on sites of superior productivity and with desired species type are managed more intensively, while other stands on sites of marginal productivity, or with non-commercial species composition, receive little or no physical intervention. Thus, within a managed forest, there can be found a mosaic of 'managed' and 'unmanaged' stands.

This report focuses on the effects of climatic changes induced by higher atmospheric concentrations of GHG such as CO_2, rather than on the direct effects of CO_2 enhancement (see Working Group I, Ecosystems, for a detailed discussion of the direct effects of CO_2 enhancement). It is accepted that important forest ecosystem effects, particularly enhanced photosynthetic rates and increased efficiency of water use, may result from increased concentrations of atmospheric CO_2 but there is no consensus on the effects on mature forest trees (Eamus and Jarvis, 1982; Jarvis, 1989). In particular, Jarvis (1989) concluded that short-term experimental results on young, pot-bound trees cannot be used to assess long-term responses of forest stands to direct CO_2 enrichment. Extrapolation to stand level effects is also not possible (Jarvis, 1989). Models for effects of climatic changes on forest stands have been constructed, however, and are being used to generate scenarios of potential forest responses to climatic changes.

3.3 World forest sector and managed forests

3.3.1 World forest sector

In 1980, forests covered about 31% of the land surface of the world (Table 2.1). Within the developed regions, the USSR and Japan have significantly higher than average areas under forest. As a group, Australia, Israel, South Africa and New Zealand are considerably below average with only 13% of their combined land areas forested. Likewise, within developing regions, the Near East and China are below average, whereas Latin America as a whole is much above average (Table 2.1). Regions with large shares of the world area of forests include North America (particularly Canada), the USSR (especially in Siberia), equatorial Africa and tropical Latin America.

3.3.2 Managed forests

Climatic changes will affect the managed forest resources of the global community to different degrees as a result of the existence of a variety of social systems and levels of political and economic development. The intensity of forest management does not necessarily parallel the level of national development. Frequently where high intensity of forest management prevails, exotic species are widely planted.

The amount of managed forest land varies widely between and within the developed and less developed countries (LDC). This suggests that impacts from climate change will affect people differently. In developed countries, the fear will be that living real fear that subsistence could be threatened. It is not possible from these data to conclude what proportion of the population relies on forests and to what degree, but there are similarities for all countries. All countries use fuelwood for heating and cooking to some extent. If the availability of wood is altered, the impacts will be most severe where alternative energy supplies are limited.

Trees also supply food for many people: date palms in tropical areas, nut pines and sugar maple in boreal and temperate areas. The forests may therefore be critical for survival, useful to augment diets or economically valuable.

Depending on the economy/environment combination, different species provide economic value to the population.

In the boreal countries, populations rely on the spruce/pine group, mostly of native origin. Temperate and tropical countries tend to rely to a greater degree on exotics such as radiata pine in New Zealand and Eucalyptus in Brazil.

Selected data from 13 nations representing all continents, Northern and Southern Hemispheres, and nations in various stages of development are illustrated in Table 2.2. The statistics in this table are based on different time periods and were collected under different methods and standards. Nevertheless, attempts have been made to base them on one currency and to relate total inventoried forest land to intensively managed forests. For example, intensively managed forests is high in New Zealand and Germany, but smaller in China and Canada.

3.4 Potential biophysical responses of forests to climate change

3.4.1 Forest protection

Many trees display a surprisingly large ability to acclimatise after long geographic transfers of seed such as occurs in provenance trials (Hall, 1989). However, each genetic unit has its ultimate limits and species are quite limited in this respect. Quantified characteristics are so far very few; some of these could be derived from the large number of seed source/provenance trials which have been established by forest research agencies over the last 80 years. This information is urgently needed for elaboration of realistic vegetation response models.

Mortality due to physical stresses is expected to increase as enhanced degrees of stand decline are experienced (Solomon, 1986; Solomon and West,1985; 1986; Auclair, 1987). If climate changes abruptly compared to the normal longevity of most tree species, many trees may not be able to survive the associated stress and consequently, competitive and pest/disease relationships could be altered. According to Smith and Tirpak (1988), climate induced declines may be seen as early as 30-60 years from now in the US Great Lakes States, 60-70 years

Table 2.1 Forest land in area in 1980. Hectare and per-caput data from Peck (1984)

Region	Total land area (million ha)	Forest land area (million ha)	Forest area proportion of total land in the region (%)	Forest area proportion of total world forests (%)	Forest land area per caput (ha/person)
World total	**13075**	**4094**	**31.3**	**100.0**	**0.9**
Developed regions	**5485**	**1829**	**33.3**	**44.7**	**1.6**
North America	1835	611	33.3	14.9	2.4
Western Europe	373	126	33.8	3.1	0.3
Eastern Europe	100	29	29.0	0.7	0.3
USSR	2227	920	41.3	22.5	3.5
Japan	37	25	67.6	0.6	0.2
Other*	913	118	12.9	2.9	2.3
Developing regions	**7591**	**2264**	**29.0**	**55.3**	**0.7**
Africa	2331	642	27.5	15.7	1.7
Near East	1192	98	8.2	2.4	0.5
China	931	116	12.5	2.8	0.1
Other Asia/Pacific	1028	356	34.6	8.7	0.3
Latin America	2020	1015	50.2	24.8	2.8
Other**	88	37	42.0	0.9	7.2

* Australia, Israel, New Zealand, South Africa

** Mainly Pacific Islands and Greenland

in the southeastern US and 30 years in the dry areas of central and western US.

Species native to cool temperate regions have been adapted to alternation ofseasons. After an active period, they become dormant and resistant to frost and drought. After a chilling period above 0°, ambient temperatures are the main driving force of dormancy release. If early winter is mild, trees may deharden and be damaged by frost in late winter. Paradoxically, a milder climate may increase the risk of frost damage. In general, the survival rhythm of trees may be broken, particularly in the far north where photoperiod is very long during the growing season.

Interactions between anthropogenic climatic changes and air pollution are particularly stressful to trees. As air pollution increases, enhanced ozone concentrations along with increased temperatures are expected to cause greater stress on plants than previously experienced. Forest degradation caused by a changing climate, enhanced ozone and other air pollution may also damage watersheds. The decline of red spruce forests in the New England states of the US over the past 100 years has been attributed to climate warming (Hamburg and Cogbill, 1988). This decline has been further exacerbated by concurrent increases in anthropogenic changes in atmospheric chemistry. In Europe where managed forests occupy a much larger portion of forest land than in North America, acidification of sensitive soils has occurred over several decades. These effects can be extrapolated from the damage already occurring on managed forests in Europe from anthropogenic air pollution.

Susceptibility to and infestations of insects and diseases is expected to increase (Pollard, 1987; Winget, 1987; Woodman, 1988; Harrington, 1989; Zoltai, 1989). For example, diseases may increase in *Pinus radiata* plantations in Australia where temperatures and precipitation increase (Booth and McMurtrie, 1989). Infestations of spruce budworm in eastern Canadian forests (Winget, 1987) and bark beetles in northwestern American forests (Pollard,1985) are expected to increase as temperatures rise.

Managed forests require that a higher level of protection be given their investment; insects and diseases cause significant losses in these forests. Distribution of insects, pests and their associated predators is closely related to climate. Damage to the northern forests by spruce budworm and bark beetles has already been attributed to recent occurrences of warmer weather (Pollard, 1985). Managed

Table 2.2 Summary of forest resources

	Indonesia	China	India	Brazil	Kenya
Forest land (million ha.)	122	135	67	565	3.7
Productive forest land (million ha.)	45	122	45	350	1.1
Managed forest (thousand ha.)	1,918*	12,733*	2.062*	3.855*	181*
Remarks					

* FAO, 1988a

	Zambia	Finland	New Zealand	Chile
Forest land (million ha.)	29.5	23.3	10.6	15.5
Productive forest land (million ha.)	4.1	18.2	2.8	4.7
Managed forest (thousand ha.)	38*	145/ann.	1200 (20/1987)	817*
Remarks		Regen. is a mean		

	Canada	USA	Austria	Germany
Forest land (million ha.)	452	265	3.2	7.3
Productive forest land (million ha.)	244	210	3.0	7.3
Managed forest (thousand ha.)	450 (1987)	917 (1980)	25 (1980)	70/ann.
Remarks	Regeneration annual mean			Regeneration annual mean

forests consisting of monocultures are expected to be even more susceptible to a particular insect or disease infestation because of the reduced genetic diversity in these forests.

The ability to respond to damage from insects and diseases varies widely from country to country. Consequently the levels of damage and loss to the various economies will be variable. Nations which rely on hard currency acquired from the sale of high quality wood could be particularly sensitive.

Fire damage is expected to increase with the susceptibility of forests (Fosberg, 1989; Street, 1989). Even if precipitation remains roughly the same, increased temperatures will lead to increased evapotranspiration and thus drier sites (see Manabe et al., 1981; Manabe and Wetherald, 1986, for supportive views, and Mitchell and Warrilow, 1987 for a contrary view). Warmer drier sites could have a higher incidence of severe fires, especially where stands are in a state of decline because of climatic changes. Likewise, the potential increases in blocking high pressure patterns, more lightning strikes and increased fuel loadings are a dangerous combination causing more and larger fires.

The ability to detect and control fires varies greatly around the world. In Canada, where prevention, detection and suppression strategies are well developed, large fires still occur. During the decade of the 1970s in Canada, the average annual area burned was one million hectares, but during the warmer 1980s this has doubled to over two million hectares. In 1989, over 6.4 million hectares of forest land were burned; fortunately, little of this was intensively managed forest. There have been suggestions that this change in the level of fire activity is the result of climatic changes in this portion of the boreal forest. It is, of course, too early to make an assumption of this type; however, the coincidence has been noticed by forest managers.

3.4.2 Shifts in climatic zones affecting forest ecosystems

Major climatic zones which govern species ranges are projected to shift under current global warming scenarios. Under a 2 x CO_2 atmosphere, conditions currently supporting boreal forests could shift north into the current tundra zone.

This would then lead to a reduction in area potentially supporting boreal forests of approximately 37%. Under this scenario, the area of subtropical forest conditions would decrease by 22%, but the rain, wet, moist, and especially dry areas of tropical forest conditions would increase by 28%.

Under conditions of rapid climatic change, existing species in their habitats will be stressed as some are better able than others to cope. There may be a net mortality in existing species, but now well adapted and intensively managed species will become more prominent in managed forested ecosystems. Because many habitats are isolated from the surrounding environment and species need continuity of habitat to move, many species may be unable to survive in their current habitats. As climate continues to change in response to human activities, the species in any given area will be increasingly asynchronous with their environment.

Shifts in tree species ranges could be important for several reasons (Moomaw, 1988). First, climate is expected to change faster than tree species can respond through migration. Second, new sites may not be edaphically hospitable, having evolved over thousands of years in a different environment. Finally, future forest climate zones leading to new forest ecosystems will not be related to current administrative boundaries which are used to defined wood supply areas, ownership, parks and nature reserves. Forests in areas of projected large climatic changes over the next 50 years will require massive readjustments, with consequent increases in the area of stressed forests (Smith and Tirpak, 1988).

For each 1°C of warming, tree ranges have the potential to expand 100 km northward while southern boundaries retreat, a process which has been tracked quite accurately since the last glaciation (Davis, 1989). The asynchrony will be greatest in the disturbed plant communities. These lags will persist a decade or two at most, then logging or fire or both, will cause a rapid adjustment to the prevailing climate. Intensively managed forests can respond to actual changes in the environment, but these could be out of synchrony with the environment unless proactive strategies are adopted that capitalise on our knowledge of anticipated climates. Depending on the rates of climatic change, stresses could increase as the environment changes, and without careful species-climate planning and allocation, the intensively managed forests could become more and more out of tune with its environment.

Miller et al. (1987) projected significant shifts in the climate suitable for loblolly pine, to the north and northeast of the current range in southeastern US. The current range may expand by almost 20% by the year 2080, with large decreases in the south and large increases to the north. The climatic habitats suitable for *Pinus radiata* and *Eucalyptus regnans,* could disappear from the Australian continent (Eckersley, 1989).

Managed forests incorporate high levels of investment with the expectation of concomitant economic returns. These forests have been established for superior quality products: teak and mahogany in tropical areas, radiata pine and Douglas fir in temperate areas, and Scots pine and black spruce in boreal forests. Impacts of climatic changes are expected to be significant on these forests and consequently on the associated economic and social systems of the dependent regions. Countries with a secure economic infrastructure will be less affected economically than those which may depend to a higher degree on forest products and have economies which are less resilient to large-scale biological damage.

3.4.3 Forest production and renewal

A variety of effects on forest productivity has been discussed (Warrick et al., 1986; Booth and McMurtrie, 1989). Increases are proposed in some cases (Kauppi and Posch, 1985; 1987) and decreased in others (eg Solomon and West, 1986). In stands where a favourable combination of climatic changes, site conditions, and stand composition and development stage exists, productivity could be enhanced. This would occur in a boreal stand on a wet site in the northern part of the boreal climate. However, productivity could decrease where moisture or nutrients are strongly limiting, or where species are already at their upper temperature or lower moisture limits.

In northern boreal forests, large areas of forested land are harvested in winter to minimise site damage. Shorter winters and/or higher temperatures will reduce the opportunity to continue this harvesting technique with consequent reduction in employment and wealth in rural communities.

Managed forests provide a variety of products (eg biomass, veneer and pulp) over a range of harvestable periods (1-2 to 100+ years). The most critical time for any plantation is during the establishment phase. During this phase, the availability of moisture controls whether or not the plantation can be established. While virtually all projections show a rise in temperature there is a greater degree of uncertainty as to the magnitude of the change and the seasonal distribution of precipitation. Changes in the amount or in the seasonal distribution of precipitation would be severe, depending on the current availability of moisture.

There are uncertainties concerning the implications of climatic changes on forest renewal because of the uncertainties in the prediction of regional climate (Woodman, 1987). It could be enhanced for species with both seed and vegetative reproductive strategies (Maini, 1988). Success rate of plantation establishment could be reduced because of increased harshness of site conditions and increased competition from other vegetation (Wheaton et al., 1987).

Marked changes in species composition could occur in the absence of intervention (Solomon et al., 1984); however, these would be determined largely by stand-level factors such as site, current stand composition and development stage, and local climatic changes. Thus, species are less limited by water availability, and near the higher latitude limit of their ranges could increase their frequency (Andrasko and Wells, 1989).

3.5 Role of forest management in potential forest responses to climatic changes

3.5.1 Managed forests

Managed stands are different in many ways from 'unmanaged' or 'less managed' stands. For example, forest land in Vietnam comprises more than 20 million hectares. On average, annual growth of the natural forest is only 1-2 m^3/hectare although pine shows a growth of 3-5 m^3/hectares. The calculation of potential productivity shows that with the same forest trees the productivity would be 10-15 x greater if the forests where intensively managed (Ngo-Si-Giai, 1989).

There are concerns in tropical America and Africa that afforestation is largely out of proportion with deforestation. Arguments for improving high-yield forest plantations, intensively managed on suitable land, have never been more justified than now (de las Salas, 1989). Understanding future climates coupled with short-rotation forestry, should make managed stands less susceptible to undesirable effects of climatic changes.

Intensive management is characterised by one or more of: species/provenance selection, planting spacing control, stand tending, one or more thinnings, protection from insects, diseases and fire and, possibly, irrigation and fertilisation. Known production forest examples are those from Venezuela (200,000 hectares of *Pinus caribaea* on lowland) and Brazil (more than 2 million hectares of Eucalyptus managed for pulp production), both on savannah landscapes (de las Salas, 1989).

There is considerable pressure to expand and intensify agricultural land in the humid tropics which, in turn, increases the demand for forest land. For example, a complete supply of wood for the production of 1 million tons of bleached short-fibre pulp a year from Eucalyptus, using the forest technology of Aracuz (Brazil), will take 90,000 hectares of forest land (Brandao, 1984).

In other countries the need for alternative energy and forest products led to the successful development of hybrid varieties and, at the same time, preserved and enhanced diversity within the gene pool of forest trees. Short-rotation forestry can fall back to a certain extent on the methods technology and experience gained from conventional plantation forestry, but under a changing climate, time is more pressing. The need for proactive management strategies within future climatic scenarios are needed to mitigate negative socioeconomic impacts of climatic changes on the forest sector. Examples of some of these accomplishments for elite plantations are particularly noteworthy (Table 2.3), including the flexibility of movement within the global environment (Table 2.4).

Intensive forest management usually entails the use of sophisticated inventory practices and forecasting tools for planning and scheduling of forest interventions compared to those employed in unmanaged forests. However, if we are unable to harvest managed stands before they become overmature, or if inadequate attention is paid to thinning schedules (Kuusela, 1987), these stands will be more susceptible to decline caused by climatic changes.

3.5.2 Agroforestry - managed forests with agriculture

The combination of livestock with trees planted for fuel, shelter and shade, fodder or fence posts is usually an ecologically sound procedure. Many successful examples exist in the American tropics. In hilly locations, however, this combination can lead to severe soil erosion. There are reports of such damage under Eucalyptus in East Africa and Ethiopia and the same can be seen in the Andean countries of South America (de las Salas, 1989).

Results from the International Research Institute for the Semi-Arid Tropics (IRISAT), India, suggest that inter-cropping can provide substantial yield increases where the shared crops compliment each other (Huda and Ong, 1989).

Table 2.3 Yields from hybrid plantation species

Location	Hybrid species	Yield (oven dry tonnes/ha/yr)
Pennsylvania, USA	poplar	8.5
Ontario, Canada	poplar	7.0
Ontario, Canada	willow	20.0
W. Kentucky, USA	black alder	7.2
Sweden	willow	22.0
Kansas, USA	silver maple	6.7
United Kingdom	willow	14.0

Source: Christopherson et al., 1989

In the central Ethiopian highlands, farmers derive multiple uses from their intercropping. They produce coffee beans, seeds, vegetables, loppable browse for their cattle and fuelwood from the branches of trees (Negah, 1989).

Budawski (1981) comments that for at least 80 years, a local alder species (*Alnus acuminata*) has been successfully planted at elevations between 1300 and 2500 m above sea level with high rainfall (200-300 mm) on good soils in the dairy region of Costa Rica. The trees are planted at wide spacings within pastures that are grazed or cut.

As populations continue to increase, there will be a greater need for integrated land use strategies to accommodate the multiple benefits of producing agricultural and forestry crops on the same shared land base.

3.5.3 Urban forests

Longridge and Mcwilliams (1989) suggest that temperature becomes increasingly important as a determinant in the survival and distribution of plants the further a plant deviates from its biological norm. Carbon partitioning to shoots and roots in response to root temperature is species dependent (Ingram et al., 1986).

Trees growing in urban areas have already spent the last 50-100 years growing under conditions of increased warming trends caused by the 'urban heat island' effect. This means that they have developed under different conditions from those same species in the natural forest. Today's urban forests, therefore, can serve as appropriate observatories for tomorrow's rural forests under a changing climate.

In temperate climates, species of *Acer, Platnus* and the *Ginkgo* are favoured as ornamentals because of their tolerance to the urban stresses. This knowledge has been gained by observation and selection, a process which may reflect the apparent tolerance to industrial pollutants, automobile exhausts, soil compaction and cultural disturbances.

The American Forestry Association (1989) estimates that planting '100 million trees could affect America's CO_2 emissions by 18 millions tons a year, saving consumers (energy conservation with shading and wind breaks) $US4 billion each year'.

3.5.4 Summary assessment of forest sensitivity to projected climatic changes

The degree to which managed forest stands are sensitive to future climatic changes depends on:

- the characteristics of the new temperature regimes. Forest ecosystems will be more sensitive with large overall increases in temperature in the northern latitudes with boreal forests and where there are temperature fluctions/extremes, or a greater frequency of non-seasonal frosts;
- the characteristics of precipitation patterns. Stands will be more sensitive if there are large changes in precipitation, especially decreases in areas currently arid and semi-arid.
- the characteristics of forest soils. Forest ecosystems will be more sensitive on more rapidly drained sites which limit tree survival and growth, such as the Mediterranean regions and North Africa; the southern boreal forest; and sites that are currently temperature-limiting on tree survival and growth such as the northern limits of boreal forest. Also at risk are forests at high elevations in North America, Europe and USSR and elsewhere.

Table 2.4 Performance of 15 species at Kaunamano, Ka'u, Hawaii Island, evaluated after 23 months (Schubert and Whiteshell, 1989)

Species and source	Growth (ht m)			Dbh (cm)	Survival (per cent)
	Mean	Range	Annual		
Eucalyptus salignia Hawaii Island, Hawaii	8.1a	2-10	4.2	6.7a	94a
Eucalyptus grandis New South Wales, Aust.	7.8a	2-11	4.1	6.7a	92a
Eucalyptus globulus Hawaii Island, Hawaii	7.3ab	2-11	3.8	6.3ab	81ab
Eucalyptus viminalis Victoria, Australia	6.6abcd	3-11	3.4	5.7abc	81ab
Eucalyptus urophylla Flores, Indonesia	6.4abcde	2-10	3.3	5.6abc	90a
Eucalyptus nitens Victoria, Australia	7.1abc	3-10	3.7	7.0a	65abc
Eucalyptus tereticornis Nigeria, West Africa	5.6bcde	2-8	2.9	4.5bcd	91a
Eucalyptus camaldulensis New South Wales, Australia	5.1def	2-8	2.7	3.8cde	66abc
Eucalyptus robusta Queensland, Australia	5.4cde	2-8	2.8	5.1abcd	93a
Eucalyptus citriodora Queenland, Australia	4.6efg	2-8	2.4	3.7cde	66abc
Albizia falcataria Sri Lanka	4.8def	3-6	2.5	6.1ab	85ab
Acacia confusa Taiwan	2.8h	2-4	1.5	2.2e	69abc
Acacia auriculaeformis India	2.9gh	2-4	1.5	2.1e	56bc
Acacia mangium Queenland, Australia	2.9gh	2-4	1.5	3.3de	47cd
Mimosa scabrella Parana, Brazil	3.4fgh	2-5	1.8	2.4e	18d

144 trees per species initially planted. Means with the same letters are not significantly different (5% level).

- the characteristics of the age of the forest. Stands in the establishment and late maturity phases will be most impacted. At the time of establishment, moisture is critical for seedlings to develop deep roots to withstand future dry periods. Juvenile stands that are free of non-tree competition, and immature and young mature stands, are more vigorous and hence resilient to environmental stress. Stands at maturity are less able to stand stress of any type and are therefore at a high risk in Canada (Woodbridge, Reed and Associates, 1988), USSR (Barr and Braden, 1988) and central Europe (Kuusela, 1987; Nilsson et al., 1989). Also susceptible to damage are those composed of species at or near the limit of their natural ranges such as the temperate deciduous forests in North America. If climatic changes are more severe for specific age classes with a stand, the chances of the stand maintaining some semblance of continuity are greater if it is an all-aged stand rather than an even-aged stand. Managed even-aged forests may have an additional risk in this respect.

The above factors do not take into account the degree to which human intervention has and can ameliorate or exacerbate stand sensitivity to climatic changes. For the moment, ignoring human intervention in forests, the forests that would seem to be most sensitive to future climatic changes include:

- boreal forests, where stands are mainly even-aged and often temperature limited, and where temperature changes are expected to be large, positive effects are probable; and

- forests in arid and semi-arid regions where increased temperatures and stable or decreasing precipitation could render sites inhospitable to continued existence of current forest stands, negative effects are probable.

3.6 Socioeconomic implications of climatic changes on forests and the forest sector

Forest products data are based largely on roundwood production, which is a common industrial output from the forest. In northern countries most of this goes to pulp and paper, whereas in the tropics the pulp and paper market is shared with the high-quality lumber market. Tropical countries rely on teak/mahogany and other valuable hardwoods.

There have been few studies of the socioeconomic effects and implications of projected climatic change on forests and the forest sector. In a recent study it would increase substantially, that growth rates in other forests of the world would increase marginally, and that Canada, Finland, Sweden and USSR would all experience increases in total exploitable forest area (Binkley, 1988). With larger inventories in northern forests, harvest rates would increase, timber prices would fall, industrial profitability in those areas would increase and new investments in production capacity would be channelled there. This would lead to an overall drop in timber prices everywhere. In general, most countries with boreal forests would witness a net increase in timber income, while most other countries would experience net decreases due to both declining harvest volumes and lower prices.

Higher costs, however,have been predicted for management interventions, especially stand establishment, in the US southeast and Pacific northwest (Regens et al., 1989). In addition, higher raw material costs have been estimated in the US southeast if climatic changes result in lower wood density of pulping timber. Other projections include:

- Significant costs associated with flooding (due to sea-level rise) of southeast US coastal loblolly pine forests and pulp/paper mills;

- lower quality and quantity of lumber yields of southern pines;

- massive costs if processing infrastructure must follow the northward and inland movement of the range of southern pines, or if log-hauling distances increase; and

- major disruptions to employment in forest sector communities, but would lie outside the southern pine range with climatic change.

Overall, Regens et al. (1989) conclude that, even though there are many opportunities for compensatory responses (ie mitigative action), the effects of climatic changes on US forest products would be negative.

Van Kooten and Arthur (1989) found that despite assumed increases in forest productivity in the boreal forests of western Canada under 2 x CO_2 climates, the welfare of Canadian forest-products producers would be reduced more than the welfare of Canadian forest-products consumers would increase. The economic benefits of the increased productivity of western Canadian forests would accrue mainly to Canada's trading partners. Contrary to these findings for Canada are the speculations of Babcock (1989) who stated that with climatic change influences on North American forests, there would be net undesirable socioeconomic impacts in the US and net desirable socioeconomic impacts in Canada.

The socioeconomic consequences of climatic changes for the world forest sector could be severe, especially where the Gross National Product has a high forestry component (Table 2.5). This conclusion is reach under a great deal of uncertainty; however, intensively managed forests have the potential to mitigate many of the anticipated undesirable impacts of climate changes. No doubt they also have the potential to intensify the effects if they are poorly designed and implemented.

Table 2.5a Summary of forest resources and forest management species (1986)

		Canada	USA	Austria	FRG
Productive forest land (million ha)		244	210	3.0	7.3
Impact of forestry on economy ($billion Cdn)	GNP	506	415,000	95	898
	Import	1.59	15.44	1.1	8.9
	Export	16.87	8.73	2.48	4.98

Managed species:

Canada: *Picea* spp., *Pinus* spp., *Abies balsamea, Populus*

USA: *Picea* spp., *Pinus* spp., *Quercus, Carya, Acer, Fagus, Betula, Ulmus*

Austria: *Picea abies, Pinus sylvestris, Larix decidua, Abiel alba, Fagus sylvatica*

Federal Republic of Germany: *Picea abies, Pinus sylvestris, Abies alba, Pseudotsuga menziesii, Larix decidua, Fagus sylvatica, Quercus robur*

		Indonesia	China	India	Brazil	Chile
Productive forest land (million ha)		45	122	45	350	4.7
Impact of forestry on economy ($billion Cdn)	GNP	85	260	246	250	16.4
	Import	0.22	3.38	0.22	0	0.16
	Export	2.00	0.68	0.2	1.22	0.48

Managed species:

Indonesia: *Meranti romin, Tectonia grandis, Pinus merkusii, Pterocarpus indicans, Eucalyptus deglupta, Acacia decurrens*

China: Dawn redwood, Cathaya, Golden Larch, Chinese swamp cypress, folkiena cedar, larches, Chinese fir, Korean pine

India: *Dipterocarpus* spp., *Shorea rubusta, Cedrus deodara, Pinus roxburghii, Abies densa, Picea smithiana*

Brazil: *Eucalyptus* spp., *Tectonia grandis, Khaya* spp., *Swietenia macrophylla*

Chile: *Pinus radiata, Eucalyptus* spp., *Populus, Pinus*

		Kenya	Zambia	Finland	New Zealand
Productive forest land (million ha)		1.1	4.1	18.2	2.8
Impact of forestry on economy ($billion Cdn)	GNP	1.7	2.1	96.9	23.2
	Import	0.02	0.09	0.4	0.16
	Export	0.004	0	7.15	0.55

Managed species:

Kenya: *Ocotea* spp., *Myrica salicifolia, Acacia labai, Acacia abyssinica, Podocarpus gracilis, Juniperus procera*

Zambia: *Brachystegia* spp., *Jubernardia angelensis, Eucalyptus grandis, Pinus kesiyia*

Finland: *Picea abies, Pinus sylvestris, Betula pendula*

New Zealand: *Pinus radiata, Podocarpus totara, Rimu compressinum, Kanaki, Rata*

Table 2.5b Roundwood production, imports, exports and their value

	Indonesia	China	India	Brazil
Roundwood production (thousand m^3)	159,768	268,835	237,774	33,763
Roundwood imports (thousand m^3)	0	12,310	27	64
Value (Cdn$000)	0	1,310,400	4,314	10,305
Roundwood exports (thousand m^3)	404	44	16	9
Value (Cdn$000)	15,984	9,644	1,213	1,538

	Kenya	Zambia	Finland	New Zealand
Roundwood production (thousand m^3)	33,763	9,946	41,297	9,341
Roundwood imports (thousand m^3)	0	9	5,258	3
Value (Cdn$000)	0	1,453	223,037	1,321
Roundwood exports (thousand m^3)	34	0	1,523	997
Value (Cdn$000)	1,274	0	157,791	54,146

	Chile	Canada	USA	Austria	FRG
Roundwood production (thousand m^3)	16,364	180,419	484,551	13,622	30,411
Roundwood imports (thousand m^3)	0	5,269	2,842	4,756	3,182
Value (Cdn$000)	0	230,132	82,904	281,899	405,908
Roundwood exports (thousand m^3)	1,169	5,068	20,410	768	4,176
Value (Cdn$000)	54,021	371,860	1,973,704	76,468	308,674

Our ability to cope with the projected impacts 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.

4 Summary and conclusions

4.1 Agriculture

4.1.1 Effects on food security

Sufficient evidence is now available from, a variety of different studies, to indicate that changes of climate would have an important effect on agriculture. Yet the fact that there are major uncertainties regarding likely effects in specific reasons should be a cause for concern. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease.

On balance, the evidence is that food production at the global level can, in the face of estimated changes of climate, be maintained at essentially the same as would have occurred without climate change, but the cost of achieving this is unclear. Moreover, there may well occur severe negative effects at the regional level, particularly in regions of high present-day vulnerability least able to adjust technically to such effects. Increases in productive potential at high mid latitudes and high latitudes, while being of regional importance, are not likely to open up large new areas for production. The gains in productive potential here due to climatic warming are unlikely to balance large-scale reductions in potential in some major grain-exporting regions at mid-latitude.

4.1.2 Magnitudes of possible dislocation

Under the estimate of changes in productive potential for a 2 x CO_2 climate outlined in this report prices of some mid-latitude crops such as maize, soy-bean and wheat could increase, reflecting a small net decrease in the global food production capability of these crops. Rice production could, however, increase if available moisture increased in Southeast Asia. The average global increase in overall production costs due to climate could thus be small (perhaps a few per cent of world agricultural GDP).

Much depends however, on how beneficial are the so-called 'direct' effects of increased CO_2 on crop yield. If plant productivity is substantially enhanced *and* more moisture is available in some major production areas, then world productive potential of staple cereals could increase relative to demand and food prices could be reduced as a result. If, on the contrary, there is little beneficial direct CO_2 effect *and* climate changes are negative for agricultural potential in all or most of the major food-exporting areas, then the average costs of world agricultural production due to climate could increase significantly, these increased costs amounting to perhaps over 10% of world agricultural GDP.

4.1.3 The most vulnerable regions and sectors

On the basis both of limited resource capacity in relation to present day population and of possible future diminution of the agricultural resource base as a consequence of reduced crop-water availability, two broad sets of regions appear most vulnerable to climatic change: (i) some semi-arid tropical and subtropical regions (viz western Arabia, the Maghreb, western West Africa, Horn of Africa and southern Africa, eastern Brazil) and (ii) some humid tropical and equatorial regions (viz southeast Asia, Central America).

In addition, certain regions that are currently net exporters of cereals could also be characterised by reduced crop-water availability and thus reduced productive potential as a result of climatic changes. Any decrease in production in these regions could markedly affect future global food prices and patterns of trade. These regions include: southern Europe, southern US, parts of South America, western Australia.

4.1.4 The effect of altered climatic extremes

Relatively small changes in the mean values of rainfall and temperature can have a marked effect on the frequency of extreme levels of available warmth and moisture. For example, the number of very hot days which can cause damaging heat stress to temperate crops could increase significantly in some regions as a result of 1° or 2°C increase in the mean annual temperatures. Similarly, reductions in average levels of soil moisture as a result of higher rates of évapotranspiration could increase substantially the number of days with a minimum threshold of water availability for given crops.

Although at present we know little about how these frequencies of extreme events may alter as a result of climatic change, the potential impact of concurrent drought or heat stress in the major food-exporting regions of the world could be severe. In addition, relatively small decreases in rainfall or increases in évapotranspiration could markedly increase both the risk and the intensity of drought in currently drought-prone (and often food-deficient) regions. Change in drought risk represents potentially the most serious impact of climatic change on agriculture both at the regional and the global level.

4.1.5 Effects on crop growth potential, land degradation, pests and diseases

Higher levels of atmospheric CO_2 are expected to enhance the growth rate of some staple cereal crops such as wheat and rice, but not of others such as millet, sorghum and maize. The use of water by crop plants may also be efficient under higher CO_2 levels. However, it is not clear how far these potentially beneficial 'direct' effects of enhanced atmospheric CO_2 will be manifested in the farmers field rather than in the experimental glasshouse.

Warming is likely to result in a poleward shift of thermal limits of agriculture, which may increase productive potential in high latitude regions. But soils and terrain may not enable much of this potential to be realised. Moreover, shifts of moisture limits in some semi-arid and subhumid regions could lead to significant reductions of potential here, with serious implications for regional food supplies in some developing countries.

There are indications that precipitation in a warmer world would be received in more intense storms at the expense at the expense of more widespread and less intense showers. This would tend to encourage higher rates of soil erosion, especially if higher rates of evaporation lead to greater differences in soil moisture between dry periods and wet periods of the year.

Temperature increases may extend the geographic range of some insect pests and insect diseases, allowing, for example, the expansion of those pests at present limited to tropical countries to current subtropical and temperate regions.

4.1.6 Regional impacts

Impacts on potential yields are likely to vary greatly according to types of climatic change and types of agriculture. In the northern mid-latitude regions where summer drying may reduce productive potential (eg in the south and central US and in southern Europe) studies have estimated yield potential to fall by ca 10-30% under an equilibrium 2 x CO_2 climate. Towards the northern edge of current core producing regions, however, warming may enhance productive potential in climatic terms. When combined with direct CO_2 effects, increased climatic potential could be substantial - though in actuality it may be limited by soils and terrain.

There are indications that warming could lead to an overall reduction of cereal production potential in North America, and to reduced potential in southern Europe but increased potential in northern Europe.

Warming could allow increased agricultural output in regions near the northern limit of current production in the USSR, but output in the Ukraine and Kazakhstan could only increase if corresponding increases in soil moisture were to occur, and this is at present uncertain.

Under the estimates of changes in climate outlined in this report, reduced output in North America, particularly of maize and soybean, would lead to increases in world prices in these crops and resultant increases in costs of livestock food and livestock products. The prices of wheat, rice and other staples would, however, depend on changes in yield potential in other major producing regions, and insufficient is known at present about possible changes of climate in these areas.

Little is known about likely impacts in semi-arid and humid tropical regions, because production potential here largely depends on crop water availability and the regional pattern of possible changes in precipitation is unclear at present. It is wise, however, to assume that crop water availability could decrease in some regions. Under these circumstances there could be substantial regional dislocation of access to food supply.

4.1.7 Rates of adaptability

In some parts of the world climatic limits to agriculture are estimated to shift poleward by 200-300 km per degree of warming (or 100 km per decade under a scenario) of a 3°C global warming by 2060. The warming-induced upward shift in thermal zones along mountain slopes would be in the order of 120-200 m.

There are indications that agriculture has an ability to adjust, within given economic and technological constraints, to a certain, limited rate of climatic change. This capability probably varies greatly between regions and sectors but no thorough analysis of adaptive capacity has yet been conducted for the agricultural sector.

In some currently highly variable climates, farmers may be more adaptable than those in regions of more equable climate. But in less developed economies, and particularly in some marginal types of agriculture, this intrinsic adaptive capability may be much less. It is important to establish in more detail the nature of this adaptability, and thus help determine critical rates of climatic change that would exceed those that could be accommodated by within-system adjustments.

4.1.8 Future tasks

This report has emphasised the inadequacy of our present knowledge. It is clear that more information on potential impacts would help us identify the full range of potentially useful responses and assist in determining which of these may be most valuable.

Some priorities for future research may be summarised as follows:

- Improved knowledge is needed of effects of changes in climate on crop yields and livestock productivity in different regions and under varying types of management. To date, less than a dozen detailed regional studies have been completed, and these are insufficient as a basis for generalising about effects on food production at the regional or world scale.

- Improved understanding is needed of the effects of changes in climate on other physical processes, for example on rates of soil erosion and salinisation; on soil nutrient depletion; on pests, diseases and soil microbes, and their vectors; on hydrological conditions as they affect irrigation water availability.

- An improved ability is required to 'scale-up' our understanding of effects on crops and livestock to effects on farm production, on village production, and on national and global food supply. This is particularly important because policies must be designed to respond to impacts at the national and global levels. Further information is needed on the effects of changes in climate on social and economic conditions in rural areas (eg employment and income, equity considerations, farm infrastructure, support services etc).

- Further information is needed on the range of potentially effective technical adjustments at the farm and village level (eg irrigation, crop selection, fertilising etc) and on the economic and political constraints on such adjustments. In particular, it is recommended that international centres of agricultural research consider the potential value of new research programs aimed at identifying or developing cultivars appropriate for altered climates.

- Further information is needed on the range of potentially effective policy responses at regional, national and international levels (eg reallocations of land use, plant breeding, improved agricultural extension schemes, large-scale water transfers etc).

4.2 Forestry - future deliberations

Countries must develop and perfect technologies to attain sustainable production from trees in all aspects, food, fodder, shelter, fuelwood and soil protection. Policy makers at all levels must be aware of the local perceptions of the use of trees, choice of species and the attitudes on management and protection of natural forest resources.

Two observations may be made. First, the problems of forest ecosystems are usually region-specific; therefore, analyses of the impacts must be region-specific. Universal issues include the conversion of all-aged multispecies, natural closed forests to high-yielding, intensively managed, mono-specific forests or to other uses including; non-forest land use, inadequately regenerated natural forest, or low-yield managed plantations. The latter three conversions often fall short of local needs in developing countries and make forest product industries vulnerable to fibre shortages while at the same time biodiversity is reduced, wildlife habitat is degraded and carbon emissions to the atmosphere increase.

The second observation concerns the uncertainty as to whether fifty years hence, these same issues will affect world forest ecosystems. The future of these forestry problems like the effects of climatic changes on the forest sector is largely dependent on society's successes or failures in addressing and solving them. Nevertheless, if these issues and tensions continue over the next 50-100 years, climatic changes might relieve or aggravate them (Table 2.5).

An initial assessment leads to the conclusion that climatic changes are more likely to exacerbate these issues and tensions than to reduce them. This finding depends on the assumption that during the next 30-50 years in response to climatic changes, forests everywhere in the world will be sensitive to some decline. If, forests in some regions are largely unaffected by climatic changes, or subject to intensive forest management resulting in increased growth rates, then many of the statements in Table 2.5 will not occur. As future climatic changes become more apparent the necessity for strong and proactive intensive forest management, agroforestry and urban forestry programs will become obvious.

The following research and assessment initiatives should be developed or pursued in the near future to reduce the level of these uncertainties.

- Studies on biological responses to various rates and magnitudes of change to obtain reliable parameters for simulation models. The genetic variability needs to be investigated simultaneously. Earlier established experiments are of special value because the final response may occur after several years of variable weather.

- Detailed regional climate scenarios are needed for the development of forest impact studies (eg see Gibbs and Hoffman, 1987; Cohen, 1989). Studies of impacts must be global in scope, international in organisation, institutional in focus and historical in breadth.

- Studies at the stand-level are a prerequisite for credible socioeconomic assessments of forest-sector responses to climate. Stand-response studies require regional climate scenarios as input, and should employ suitable stand-dynamics simulators (eg Pastor and Post, 1985; 1986; 1988).

- Better understanding of the relationship between species and sites is required. Progress is being made in identifying and mapping the climatically suitable and sustainable areas for a wide variety of tree species (eg Booth et al., 1989).

- Improved knowledge is required concerning the potential role of forest management at the management unit scale, in mitigating undesirable impacts and capitalising on desirable impacts due to climatic change. In industrial forests, management units are composed of several thousand stands and cover 10^5-10^6 ha. Forest-level analyses require inputs from stand-scale models employing suitable forest-dynamics simulators (eg Attebring et al., 1988; Wang et al., 1987).

- Analyses are required at the regional-scale (10^5 ha +) of the possible effects on wildlife habitat and recreational potential resulting from climate-induced forest-structure changes. These studies require scenarios of the dynamics of wildlife habitat, which can be developed using forest simulators as noted above.

- Analyses are required at the regional scale (10^7 ha +) of the potential socioeconomic repercussions on rural communities, industrial concerns, markets and trade in forest products, and on governments, resulting from timber-supply fluctuations due to climatic change.

- Socioeconomic impacts should focus on the transitional climate that may occur over the next several decades, rather than on a single future long-term 'equilibrium' climate.
- In the face of great uncertainties about rates and magnitudes of climatic changes, forest responses to potential climatic change and socioeconomic repercussions of climate induced forest changes,

it is prudent to prepare for severe undesirable impacts to ensure that viable and flexible options are implemented to maintain sustainable forest ecosystems.

- The relationships between rates of biophysical processes, socioeconomic and technological processes must be known in order to understand and respond satisfactorily to socioeconomic impacts of climatic changes on the forest sector.

Examining biogeochemical changes on a global scale is so complex that adding humans as an additional variable further complicates the issue; nevertheless, humans are the critical element in the study of ecological systems. We must consider the institutional imperatives, and the economic and political influences on people in different nations with the cultural diversity that distinguishes and may dominate our actions.

Figure 2.1 Sensitivity of world agricultural prices to yield changes

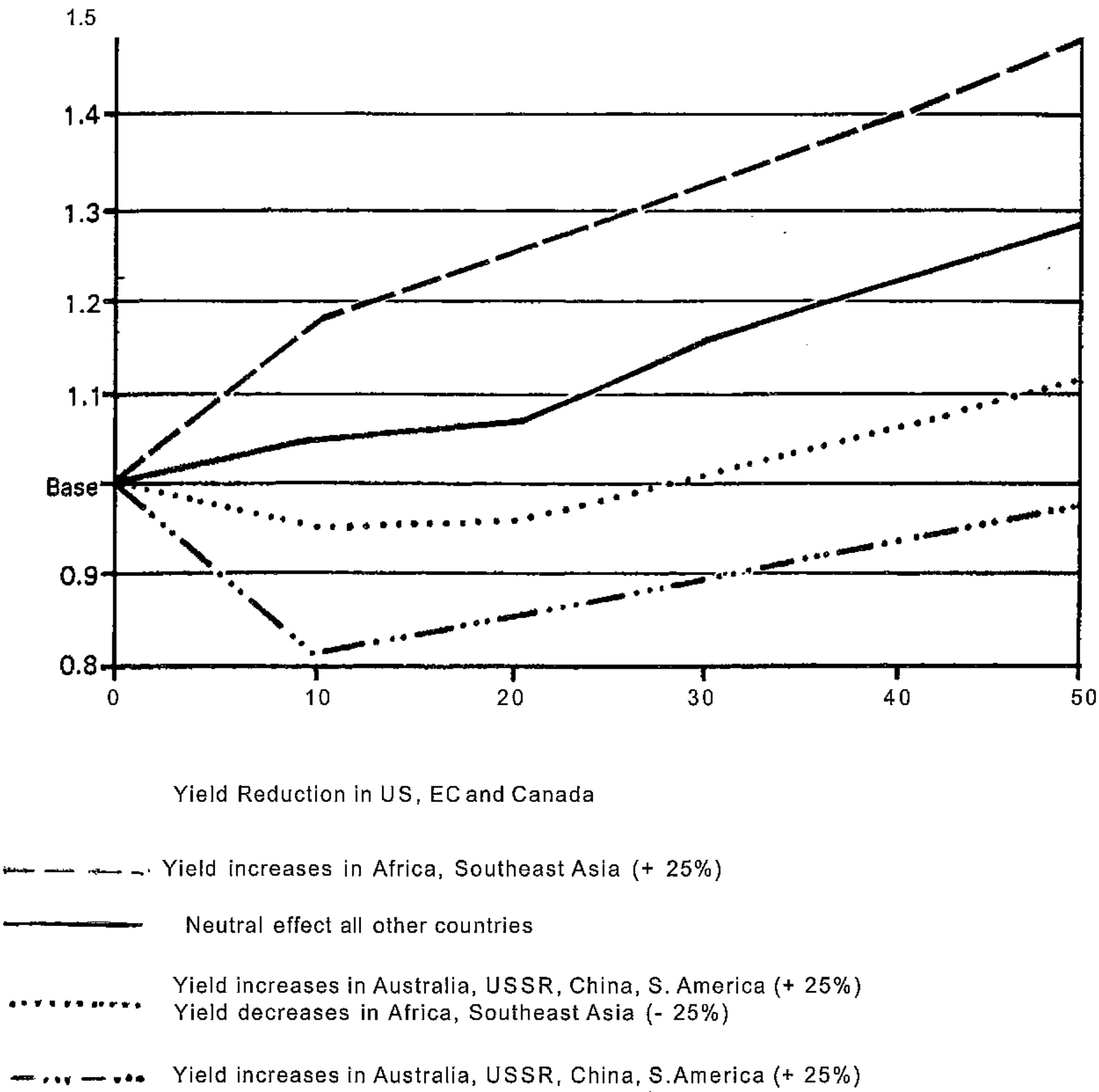

Figure 2.1 Estimated changes in price of agricultural commodities for a range **of** concurrent yield reductions in USA, the European Community and Canada. **The** estimations are for four scenarios: 1) no change elsewhere; 2) yield increases of 25% in Africa and SE Asia, but no change in other countries; 3) yield **increases** of 25% in Australia, USSR, China, S. America and decreases of 25% in **Africa and** SE Asia; and 4) yield increases in Australia, USSR, China and S. America, but **no change** in other countries. The estimations assume present-day economic conditions **and** technology (Kane, et al., 1 989)

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Chapter 3

Natural terrestrial ecosystems

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1 Introduction

This report examines the ecological impacts of climate change on natural ecosystems (land areas and associated flora and fauna which are not intensively managed) and the socioeconomic consequences of these impacts. For this report, the definition of natural terrestrial ecosystems includes unmanaged forests and other natural vegetation systems, wetlands, deserts, freshwater lakes, alpine regions and protected areas such as natural heritage sites and reserves. It does not include intensively managed ecosystems such as agricultural areas and forest plantations (Chapter 2, Agriculture and forestry) nor does it include components of the terrestrial cryosphere (Chapter 7, Seasonal snow cover, ice and permafrost).

The changes to climate are considered to be those resulting from increased atmospheric concentrations of greenhouse gases (GHG). The climate change scenarios that form the base reference for this report are generally those decided at the workshop held in Villach during 1987 (WMO, 1988). The illustrative examples of the environmental impacts and socioeconomic consequences, however, may be based on different scenarios.

Generally accepted vegetation zones (eg warm desert, tropical forest, boreal forest and tundra) have been used to stratify the discussions. Use of these zones recognises the spatial resolution limitations of the current understanding of global climate change and the likely responses of ecosystems and their components. Further stratification is achieved by focusing discussion on major and sensitive components of natural terrestrial ecosystems: biodiversity and endangered species, unmanaged forests and vegetation, wetlands, freshwater fisheries, wildlife and heritage sites and reserves. Although the focus will be on the larger scale (approximately 1000 km), where available, local analyses will be used to illustrate specific environmental impacts and socioeconomic consequences.

1.1 Reasons for concern

Climate is naturally subject to long-term changes (glacial and interglacial periods) and short-term fluctuations. Scientific and technological progress, however, appears poised to accelerate climate evolution significantly by increasing the atmospheric concentration of radiatively active gases. The associated enhancement of the greenhouse effect has reached the level at which these anthropogenic increases in GHG gases have the potential to affect global climate.

The increases in the atmospheric concentrations of GHG and the projected changes in climate resulting from these increases pose a serious threat to natural terrestrial ecosystems and associated socioeconomic systems. It must be recognised that the temperature changes suggested by climate scenarios would present natural systems with a warmer climate than has been experienced at least during the past 100,000 years (Schneider and Londer, 1984), and that there is no equivalent during the period of recent development of the present vegetation. Moreover, a global temperature rise of 4°C above the present norm, for example, would make the earth its warmest since the Eocene, 40 million years ago (Barron, 1985; Webb, 1990).

Such warming would not only be greater than recent natural fluctuations, but it would occur 15 to 40 times faster than past natural changes (Schneider, 1989; Gleick et al., 1990). Such a rate of change may exceed the ability of many species to adapt or disperse into more favourable regions and many plant and animal species may become extinct (Lester and Myers, 1989; Pain, 1988). For widespread, abundant species, such as the loblolly pine ***(Pinus taeda)*** (Miller et al., 1987), even a substantial range retraction might not threaten extinction; however, rare localised species, whose entire ranges become unsuitable, would be extinguished unless migration or human interventions were successful. On the other hand, some species, rare or abundant, may thrive under a new climate regime. Even for widely distributed species, major losses of important ecotypes and associated genetic material is likely (Davis and Zabinski, 1990).

Temperature changes will be important for animals and also insects. Mean temperature, for example, influences the ratios of males to females in some reptiles. Changes in extreme temperatures, such as freezing versus no freezing, or extreme high temperatures, can significantly effect the dynamics and distribution of animals and, in particular, insects (Waller et al., 1989).

Ecological stress will not be caused by temperature changes alone. Global precipitation characteristics are also expected to change (Hansen et al., 1981; Kellogg and Schware, 1981; Manabe and Wetherald, 1987; Schlesinger and Mitchell, 1987) and for many species, precipitation and soil moisture are more important determinants of survival than temperature. Indeed, except at the treeline, where minimum temperature is often the dominant limiting factor, precipitation plays a major role in determining the distribution of vegetation with trees occurring mainly where annual amounts are in excess of 300 mm (Woodward, 1990). Complicating this response is the fact that enhanced levels of atmospheric CO_2 increases the water use efficiency of plants (Gifford, 1979). Therefore, although precipitation characteristics are expected to change, plants' efficiency in the use of the available moisture will also change.

The breeding success of birds and small mammals (eg muskrats, beavers, weasels, reptilia, and amphibians) are often linked to seasonal precipitation, snow cover and snowmelt (eg Campbell, 1968; Davis and Cook, 1983). Small alterations in the amount, timing and intensity of precipitation events can dramatically affect regional water balances, with significant impacts on flora and fauna (Pain, 1988; Kushlan, 1986).

Other factors, important in determining species distribution and health, are expected to change in response to the proposed global warming. Soil chemistry could change (Kellison and Weir, 1987) as a result of both climatic changes and of associated changes in storm patterns that could alter soil process, including leaching and erosion rates (Harte et al., 1990). Sea-levels may rise, inundating coastal biological communities (NRC, 1983; Hansen et al., 1981; Hoffman et al., 1983; Titus et al., 1984). Projected changes in fire frequency and severity, particularly during ecosystem transitional periods, could alter the structure of ecosystems and play a dominant role in species dispersal.

In addition, many wildlife species have become increasingly dependent on habitats modified by people. Their responses to climatic changes, therefore, will, in many cases, be reactions to human responses (eg changes in land use and urban development) which are also affected by climatic changes (Burger, 1984). Moreover, encroachment, barriers and habitat destruction by humans, with no analog to past periods of climate change, would probably place populations of many species in jeopardy. Topping and Bond (1988) and Lester and Myers (1989) maintain that the direct physical and physiological effects of an increase in air and water temperature on wildlife will be less significant than the indirect effects such as habitat transformation, wetland loss, salt marsh intrusion, estuarine changes and loss of food sources.

An important point in understanding species' response to climate change, is that weather is variable and extreme events, like droughts, frosts, floods, blizzards, the frequency of hot or cold spells and associated fires and pest outbreaks, may have more effect on species distributions than average climate (eg Knopf and Sedgwick, 1987). Animals can adapt their behaviour during droughts and heatwaves by timing activity to cooler parts of the day, restricting their movements to conserve energy and water, or migrating to more favourable areas. Increased frequency or persistence of these conditions, however, can significantly influence an animal's health and survival either directly or indirectly through loss of habitat, food and water.

Increasing concentrations of GHG in the atmosphere pose two different sorts of stresses on natural terrestrial ecosystems. In addition to causing changes in climate, GHG can directly affect ecosystem processes, thereby influencing ecosystem health and composition. Primarily affected are biological and geomorphological processes (eg photosynthesis and decomposition) which alter nutrient availability, reproduction and biomass productivity. Changes in these basic ecosystem processes alone can have a significant impact on the composition and health of the ecosystem through changes in competition, habitat conditions and food availability.

Another factor to be taken into consideration when examining the impacts of climate change on natural terrestrial ecosystems is the manner by which changes to ecosystems can affect the climate (ie through feedback mechanisms). There are at least two such feedback mechanisms. One relates to the fact that changes in ecosystems can alter the albedo and hydrological characteristics of an area, thereby affecting the local energy and water balance. The second mechanism is a result of the manner in which gases are exchanged between the biosphere and the atmosphere. Ecosystems can either enhance the greenhouse effect by increasing their emissions of certain gases (eg methane), or decreasing their effectiveness as a sink for these gases (Steudler et al., 1989). These feedback mechanisms are dealt with in detail by Working Group I, Subgroup X.

Although changes to natural terrestrial ecosystems as a result of climate change are often viewed negatively, many areas could benefit ecologically, socially and/or economically from the suggested changes. Recognising and responding to these 'positive' effects, however, will pose some problems. Difficulties will arise when trying to identify whether or not a particular change (or combination of changes) is having, or will have, beneficial effects on an ecosystem. In addition, identifying the appropriate action and being able and willing to take advantage of the opportunity and promote the change(s) will also be problematic.

1.2 Sensitive species and ecosystems

Those species which are particularly sensitive (ie those which are most at risk and which could be the first to be affected) to climatic changes (Peters and Darling, 1985) are:

- species at the edge of (or beyond) their 'optimal' range;
- geographically localised species (eg those found on islands, on mountain peaks, in remnant vegetation patches in rural areas, and in reserves and parks);
- genetically impoverished species - specialised organisms with highly specialised niches (less tolerant of ecological changes (Kirkham, 1988));
- poor dispersers;
- species which reproduce more slowly; and
- localised populations of annual species (failure to reproduce one year could result in their extinction).

This would suggest that montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves may be particularly at risk. Their component species may not be able to survive or adapt to climatic changes because of the limited number of options available to them.

Island ecosystems, because of the barrier provided by surrounding water and with their higher ratio of endemism, are at risk of disruption as a result of projected climatic changes. Small oceanic islands are particularly at risk since recovery could be slow and, in some cases, may require massive human interventions. The effect on individual species would depend on their specific climatic tolerances and other factors, such as the existence of prey and predators.

The artificial boundaries and isolation of heritage sites and reserves may enhance their sensitivity. These areas are scattered throughout the world and range from isolated wilderness to areas that are heavily used by visitors and residents in many cases. The philosophy of managing these areas varies widely and the level of management currently ranges from monitoring to massive intervention. Heritage sites and reserves are already subject to many types of stress and pressures. For instance, Connelly (1982) identified 73 different types of stress. Half of these arise from sources outside the parks. Current threats include aesthetic degradation, air and water pollution, fire, insects and diseases, industrial impact, removal of resources, exotic species encroachment and even park operations. The effects of climate change on these pressure is not known.

Migratory birds and animals present an intriguing and complex set of problems in terms of assessing the impacts of global climate change. Through their seasonal movements, they often cover vast areas and cross a number of major biomes. Climate-induced changes in any of the critical habitats along their migration routes will have important consequences which may escape explanation until events over all parts of their range have been observed.

1.3 Analytical methodologies

Inferences about the impacts of elevated GHG and an altered climate on natural terrestrial ecosystems have come from four sources: (i) analysis of the current bioclimatic distributions of vegetation types and their possible future distributions as climatic patterns change (direct transfer function approach); (ii) analyses of historical vegetational changes under past climatic conditions (palaeoreconstruction approach); (iii) simulation modelling of ecosystems at a stand level; and (iv) reasoning from a knowledge of the ecophysiology of dominant plant species and associated growth-chamber experiments and knowledge of the ecological requirements of animal species. Each of these methods of inferring impacts has its strengths and weaknesses. What would be useful but is lacking, however, are long-term observations of the response of ecosystems to altered GHG (Oechel, 1989) and climatic conditions outside the controlled research environment. This also includes field experiments involving transplanting of intact vegetation mats from colder to warmer vegetation zones and in areas with high topographical diversity. In the absence of such information, scientists are left with very imperfect means of assessments, particularly of the secondary and combined influences of several stressors (eg climate, fire and air pollution) on the interacting components of ecosystems (vegetation, wildlife, pests and pathogens, soil nutrients, and water and air quality).

The direct transfer function approach has several shortcomings: (i) species respond to climatic change according to their individual tolerances; consequently vegetation assemblages as we currently know them will not move as a unit to new locations as climate changes (Davis et al., 1986; Huntley and Webb, 1989; Westman and Malanson, in press); (ii) the response of species to the combined effects of altered climate and altered GHG are not considered; most notably and direct CGyfertilisation effect will probably alter vegetation responses to temperature, precipitation and other climatic features; (iii) interactive effects of climate change on other factors such as wildfire frequency, air pollution, herbivory and pathogenicity are not considered (these interactive effects may be particularly critical during periods of rapid ecosystem transition); (iv) the impacts of barriers to migration, including urbanisation and topographical barriers and differing substrate (ie soil) types in the new locations, are not considered; and (v) differing rates of species dispersal and migration can result in shifting assemblages. In this last case, key pollinators, symbiots, or other critical link species, may be absent, resulting in impoverished and possibly less stable communities.

The use of palaeoreconstruction scenarios to infer potential responses is limited since (i) the projected amount and rate of climate change are unprecedented, (ii) CO_2 variations, although occurring in the past, were not the causes of these past climatic changes; (iii) given dating uncertainty, data from the Hypsithermal are from a 2000-year or longer time interval; and (iv) the actual mean global temperature 6000 years bp, 125,000 years bp or in the Pliocene of 1°C, 2°C and 3°C are only rough estimates at this time. Furthermore, the suggested climatic changes will occur along with other pressures (eg air and water pollution, and human population growth) that are unprecedented in earlier periods of climate history. This suggests that palaeo-based scenarios for species migration may give relevant indications of the mechanisms and patterns of dispersal but not of the rate.

Simulation models are a limited tool because they are vastly simplified representations of ecosystem processes involved. In addition, they generally do not examine interactions at a landscape level (eg migration, dispersal, fire, pest and pathogen spread, substrate change), nor do they incorporate interactive effects of changing fire frequency, air quality, elevated GHG and pest potential on a multispecies perennial community. Some research has begun to move in that direction (eg Pastor and Post, 1988; Malanson and Westman, in press), but results of sophisticated models are some years away. Furthermore, full validation of model results cannot be achieved until the results of long-term studies in a field setting are available.

Reasoning from ecophysiological understanding is limited because (i) the long-term effects of elevated GHG and elevated temperature on many natural terrestrial ecosystems are not known; and (ii) such an approach cannot account for interactive effects in ecosystems (eg competition and herbivory).

These shortcomings help to explain why assessing the ecological and socioeconomic consequences of climatic changes for natural terrestrial ecosystems is currently a highly speculative endeavour, despite the research conducted to date.

1.4 Historical evidence

The response of biota to climate change can be inferred by observing present and past distributions of plants and animals, which are sensitive to critical levels of heat and moisture (Colinvaux, 1986). For example, one race of the dwarf birch ***(Betula nana)*** can grow only where the temperature never exceeds 22°C (Ford, 1982), suggesting that it would disappear from much of its range when global warming causes temperatures to exceed this limit. Recent historical observations of changes in range of species dominance, such as observations of the gradual replacement of red spruce ***(Picea rubens)*** by deciduous species during the past 180 years in the eastern US (Hamburg and Cogbill, 1988), can be used to suggest future responses of the observed species to changes in climate. It must also be recognised that over the long term, climatic change may trigger genetic responses, creating divergent races of species to respond to newly evolving niches.

Insight into long-term responses to large climatic changes can be gleaned from studies of fossil distributions of, particularly, pollen (Davis, 1983) and small mammals (Graham, 1986). Such observations tell us that plants and animals are sensitive to climate. Their ranges move when the climate patterns change - species die out in areas where they were once found and colonise new areas where the climate becomes more suitable. Based on palaeoreconstruction scenarios, however, future changes in climate will have strongly diverging impacts on natural terrestrial ecosystems rather than unequivocal tendencies.

The manner and the intensity in which ecosystems respond to changes in climate differ from ecosystem to ecosystem and from species to species. Some species will benefit and others will risk extinction (Topping and Bond, 1988). Historical evidence suggests that in those situations where the changes in climate were dramatic (ie changes were large, long lasting or occurred relatively quickly), the responses of ecosystems were relatively well defined. Less pronounced changes in climate have caused regionally different, sometimes retarded, reactions by ecosystems, and in still other cases, had no impact at all (eg the responses of ecosystems in northern central Europe relative to the lack of response in southern central Europe as a result of the cold spell of the so-called Younger Dryas of 11,000 to 10,300 bp).

Responses similar to those mentioned above can be expected during the next 50-100 years as an early response to projected climatic changes, including disruption of natural community and extinction of population and species. Even many animal species that are currently widespread could experience large range changes. Efficient dispersers may be able to shift their ranges to take advantage of newly suitable habitat, but most species will at best experience a time lag before extensive colonisation is possible, and hence in the short term may shown range diminishment. At worst, many species will never be able to recover without human intervention since migration routes are cut off by development (eg farm fences, fields, highways and other barriers) or other human-caused habitat loss (Lewis, 1987).

2 Direct impacts of elevated CO_2

Carbon, an element essential to life, is primarily available to terrestrial plants (and other organisms) in the form of atmospheric CO_2. Increased concentration of atmospheric CO_2, especially where it is a limiting factor can modify the physiological behaviour of plants. The nature of plant responses to enhance ambient CO_2 concentration is quite complex (see Working Group I Report, Ecosystems, for detailed discussions) with first-order and second-order effects. First-order effects include (Strain and Cure, 1985) potential impacts on photosynthesis, respiration, water use efficiency, reproduction, tolerance to salinity, and growth rates (CO_2 fertilisation) and form. The second-order effects include plant-to-plant interactions (eg competition and symbiosis), plant-to-animal interactions (eg herbivory, pollination and shelter) and plant-to-microbial interactions (eg disease and decomposition).

A wide range of possible responses by natural terrestrial ecosystems to enhance ambient CO_2 concentrations have been hypothesised including, for some plants and organisms, increased photosynthesis rates, growth rates, productivity and water use efficiency. When the ambient CO_2 concentration changes, the physiological responses of plants and organisms to other factors, including climatic changes can be modified. Improved water and nutrient use efficiency of some species of trees due to elevated CO_2 in the atmosphere, for example, may ameliorate their projected decline and mortality. These responses, however, will not be universal, with their degree and nature dependent not only on plant species and variety, but also on location, nutrient and water status, and development stage.

The use of the existing hypotheses to predict ecosystem responses is limited because of the small database on which they are founded. No study of plant responses to enhanced ambient CO_2 concentration have used domestic species with the results extrapolated to natural species and a length of exposure limited to days or one growing season. Recent studies (eg Oechel, 1989, working in the tussock tundra at Toolik Lake in Alaska) have found that vegetation may rapidly adjust to elevated CO_2 with the initial increases in photosynthetic rate decreasing and returning to near-normal levels over time.

Further limiting the applicability of experimental results to natural terrestrial ecosystems is the fact that, so far, the majority of the experiments are conducted in artificial environments with herbivores and pathogens excluded, extremes of temperature and light avoided, and water and nutrients not limited (except in those experiments where these are intentionally varied). Furthermore, in most experiments, only one species and only juvenile specimens of these (eg seedlings) are studied.

The potential positive effects of CO_2 enrichment may be reduced by other anthropogenic-caused changes in atmospheric chemistry (eg ozone), ecosystem feedbacks, competition for limited nutrients and/or water, and the influence of temperature on photosynthesis and respiration. Izrael and Semenov (1990), for example, found that observed increases in productivity as a result of enhanced CO_2 concentrations cannot be suppressed only by enhanced levels of ozone (ozone pollution levels used are similar to those currently found in industrial areas of North America and Europe) but also could override their projected increases and result in significant decreases in productivity.

Potential influences of elevated CO_2 on natural terrestrial ecosystems that may impact on ecosystem structure and process and thus also influence the ecosystems responses to other forcing factors such as climatic changes include:

- net primary productivity, particularly the potential differential responses of associated and invading species;

- time for plant species to reach maturity and the implications for reproduction;

- relative responsiveness of herbaceous weed and fast-growing hardwood (Pollard, 1989) as compared with traditionally more 'desirable' species;

- reduction in nutrient quality of vegetation and the resulting need for herbivores, especially insects to consume more;

- ratio of seed to vegetative growth; and

- soil processes.

3 Changes in the boundaries of vegetation zones

One response of natural terrestrial ecosystems to changes in climate and GHG concentrations is to change the distribution of flora and fauna. This is essentially a two-step process; first, the climate zone will shift, and conditions for species may become more or less favourable; second, the species may follow the climatic region. The time lags in each of the two steps between cause and effect could be short or long, ranging from a few years or decades to a century. The shorter the lag, the less ability species will have to adapt and the greater the potential impacts and associated socioeconomic consequences. It should be understood that abiotic factors such as climate, are not the only determinant of whether or not a species exists at a particular location. Such factors as how well as a species is established, competition, predators and prey, and the viability of invading species, and how these are also influenced by climatic change need also to be considered. Not surprisingly, species tend to track their climatic zones, retracting their ranges where conditions become unsuitable while expanding them where conditions improve (Peters and Darling, 1985; Ford, 1982). Even very small temperature changes within this century have been observed to cause substantial range changes for certain species (Ford, 1982; Kullman, 1983).

Changes in the geographical distribution of climatic zones associated with ecosystems and in their composition are complicated by the fact that supporting data are limited or, in the case of many species, non-existent. Some vegetation types will be able to adapt to change more than others depending, among other factors, on the strength of the controlling climatic factor relative to other controlling factors; on the relative status of each vegetation type in the local dynamic sequence, their stability and resilience; and on the impact of human activities and interventions. The ability of species to move in response to a changing climate depends on their ability to disperse (eg their reproductive capability, seed dispersal, availability of migration corridors and mobility), the mobility of accompanying species (eg food, competition, and predator-prey relationships), the frequency of disturbances (eg fire) and the availability of suitable habitat. Knowledge of a species' natural history, particularly its climatic range, is often insufficient for an accurate prediction of a change in geographic range in response to climatic changes. Because of the complexity of the determining factors, species' and their ecosystems' responses will not be simple. They will vary from a progressive, uniform dispersion to sudden spurts with great leaps forward (Mooney and Drake, 1989).

Interspecific interactions altered by climatic change will have a major role in determining new species' distributions. Temperature, for example, can influence predation rates (Rand, 1964), parasitism (Aho et al., 1976) and competitive interactions (Beauchamp and Ullyott, 1932), disturbances and disease incidence, all of which play a significant role in determining ecosystem structure.

Past vegetation regions have shifted in response to temperature changes of a similar magnitude as that which is expected to occur during the next 100 years or less (Baker 1983; Bernabo and Webb, 1977; Butzer, 1980; Flohn, 1979; Muller, 1979; Van Devender and Spaulding, 1979; COHMAP members, 1988). These migrations, however, occurred over thousands of years rather than within a few decades as projected climatic changes may necessitate. In the past, as the earth warmed, species tended to migrate to higher latitudes, colonising new habitats closer to the poles (Payette and Filion, 1985), often while their ranges contracted away from the equator as conditions there became unsuitable and other species migrated to these areas. Studies indicate, however, that species can spread in any direction once they become established in a particular region (Birks, 1989).

During several Pleistocene interglacials, the mean annual temperature in North America was apparently 2°-3°C higher than now. Sweet gum trees ***(Liquidambar)*** grew in southern Ontario (Wright, 1971); Osage oranges ***(Madura)*** and papaws ***(Asimina)*** grew several hundred kilometres north of their present distributions; manatees swam in New Jersey; and tapirs and peccaries foraged in North Carolina (Dorf, 1976). During the last of these interglacials, which ended more than 125,000 years bp, vegetation in northwestern Europe, which is now taiga, was predominantly temperate forest (Critchfield, 1980). Other significant changes in species' ranges have been caused by altered precipitation accompanying past global warming, including expansion of prairie in the American Midwest during the hypsithermal approximately 7000 years bp (Bernabo and Webb, 1977).

While individual species tend to shift in the same general direction, entire biological communities do not move in synchrony. On the contrary, since species shift at different rates in response to climate change, communities often disassociate into their component species. Recent studies of fossil packrat ***{Neotoma spp.)*** middens in the southwestern US show that during the wetter, warmer climate of 22,000-12,000 years bp, there was no concerted shift of plant communities as a whole. Instead, species responded individually to climatic change, forming stable but, by present-day standards, unusual assemblages of plants and animals (Van Devender and Spaulding, 1979). In eastern North America, too, post-glacial communities were often ephemeral associations of species, changing as individual ranges changed (Davis, 1983; Graham, 1986).

Another aspect of species response is that species may shift altitudinally as well as latitudinally. When the climate warms, species may shift to higher elevations. Generally, a short rise in altitude corresponds to a major shift in latitude (3°C cooling over 500 m in elevation equals roughly 250 km in latitude (MacArthur, 1972)). Thus, during the middle Holocene (hypsithermal) 6000 years bp, when temperatures in eastern North America were 2°C warmer than at present, hemlock ***{Tsuga canadensis)*** and white pine ***(Pinus strobus)*** were found 350 m higher on mountains than they are today (Davis, 1983).

In plants, excessive heat and associated decreases in soil moisture may impair chances for survival and reproduction. Coniferous seedlings, for example, are injured by soil surface temperatures over 45°C, although other types of plants can tolerate much higher temperatures (Daubenmire, 1962). Many plants have their northern limits determined by minimum temperature isotherms below which some key physiological process does not occur. For instance, the grey hair grass ***(Corynephorus canescens)*** is largely unsuccessful at germinating seeds below 15°C and is bounded to the north by the 15°C July mean isotherm (Marshall, 1978).

Some species in Western Europe are distinctly coastal owing to their sensitivity to winter frost. The most typical are holly ***{Ilex aquifolium),*** bell-heather ***{Erica cinerea)*** and slender St John's wort ***{Hypericumpulchrum),*** all having eastern boundaries in Europe well correlated with the position of the January isotherms. Frost-sensitive species are likely to have a general expansion under climatic change (Holten, 1990a,b). Other plant species in the same region seem to be disfavoured by mild winters, avoiding the lowlands of Western Europe. These species very often have a complementary distribution to the above-mentioned frost-sensitive species. Many of them belong to the dark taiga of western Siberia. These species which in Scandinavia, include Norway spruce ***{Picea abies)*** and tall herb species like ***Aconitum septentrional*** will probably move eastward if winter temperatures increase 3°-4°C.

Moisture extremes exceeding physiological tolerances also determine species' distributions. The European range of the beech tree ***{Fagus sylvaticd)*** ends in the south where rainfall is less than 600 mm annually (Seddon, 1971). Dog's mercury ***{Mercurialis perennis),*** a herb restricted to well-drained sites in Britain, cannot survive in soil where the water table reaches as high as 10 cm below the soil surface (Ford, 1982).

Since the biogeographical distributions of many wetland species are temperature-limited (eg Spartina and mangrove species in coastal wetlands), any increase in average temperature would, in principle, permit the migration of such species into new areas, thus altering the structure and composition of many wetland areas. In some cases this might be viewed as a benefit, in others a detriment. Noxious weeds, such as water hyacinth ***{Eichhornia crasspipes),*** water lettuce ***{Pistia stratiotes),*** purple loosestrife ***{Lythrum salicaria)*** and African pyle ***{Salvinia molestd),*** infest many wetland areas. Where these species are temperature-limited, expansion of their ranges can be expected in response to climate change with detrimental impact to the species diversity and value of many wetlands.

Many animals have the potential to react quickly to environmental changes; however, the responses of associated plant communities can be relatively slow, causing loss and fragmentation of habitat (Peters and Darling, 1985; Arnold, 1985) with existing problems of habitat loss becoming more serious (Topping and Bond, 1988). Natural physical barriers such as mountain ranges, large bodies of water and deserts can also restrict movement of species. In these cases migration is not a viable alternative. For example, the Yucatan Peninsula is essentially a biogeographical trap in which extinction rates could be abnormally high should suggested changes in climate occur. Suggested wetter conditions over the Yucatan Peninsula (Menchaca and Byrne, 1990) would effectively eliminate areas of seasonally dry woodlands and scrub. This trend towards a wetter climate could also lead to the extinction of the more drought-adapted species of the disjunct desert basins of Hidalgo and Puebla in Mexico, as these desert areas are separated from each other and from the deserts of the north by intervening mountain ranges.

From a biogeographical point of view, the Fennoscandian Peninsula is an 'island' as far as the migration of some southern and thermophilous species of plants and animals are concerned. On their migration northward, they will meet both physical barriers (seas, fjords, mountains) and anthropogenic barriers (cultivated fields, forest plantations and clearcut areas) (Holton, 1990 a,b), and some may not reach the Fennoscandian Peninsula before their extinction, if climate changes too rapidly.

If a species' intrinsic colonisation ability is low, or if barriers to dispersal are present, extinction may result if present habitats becomes unsuitable. Most likely to survive are those animals and plants which normally disperse over relatively long distances or those that can survive in a wide range of habitats. This includes animals that migrate great distances on land or in the air, those animals (such as ticks) and seeds carried by animals (Cubberly, 1989) and light, wind-carried seeds. Non-migrating species with restricted distribution and narrow ecological requirements may be more vulnerable (Bean, 1989) unless climate change favours their habitat.

There are many cases where complete or local extinction has occurred because species were unable to disperse rapidly enough when climate changed over a long period of time. For example, a large diverse group of plant genera, including water-shield ***(Brassenia),*** sweet gum ***(Liquidambar),*** tulip tree ***(Liriodendron),*** magnolia ***(Magnolia),*** moonseed ***(Menispermum),*** hemlock ***(Tsuga),*** arbor vitae ***(Thuja),*** and white cedar ***(Chamaecyparis),*** had a circumpolar distribution in the Tertiary (Tralau, 1973). During the Pleistocene ice ages, they became extinct in Europe while surviving in North America, presumably because of the east-west orientation of such barriers as the Pyrenees, Alps, and the Mediterranean, which blocked southward migration (Tralau, 1973).

Although in theory many animals may be highly mobile, the distribution of some is limited by the distributions of particular plants needed for food or shelter. Behaviour may also restrict dispersal even of animals physically capable of large movements. Dispersal rates below 2 km/year have been measured for several species of deer (Rapoport, 1982), and many tropical deep-forest birds simply do not cross even very small unforested areas (Diamond, 1975; Peters and Darling, 1985). On the other hand, some highly mobile animals may shift rapidly, as have some European birds (Edgell, 1984).

Other species of plants and animals thrived in Europe during the cold periods, but could not survive conditions in post-glacial forests (eg large antlered ungulates). A previously widespread dung beetle ***(Alphodius hodereri)*** is now extinct throughout the world except in the high Tibetan plateau where conditions remain cold enough for its survival (Cox and Moore, 1985). Other species, like the Norwegian mugwort ***(Artemisia novegica)*** and the springtail ***(Tetracanthella árctica)*** now Uve primarily in the boreal zone but also survive in a few cold, mountaintop refugia in temperate Europe (Cox and Moore, 1985).

Although some species, such as plants propagated by spores or 'dust' seeds, may be able to match these rates (Perring, 1965), many species probably could not disperse fast enough to compensate for the proposed climate change without human assistance (Rapoport, 1982), particularly given the presence of dispersal barriers. Contrary to migration of species during previously warm periods, modern species' migration may be severely restricted by human land uses which have created significant barriers. An additional factor is that suitable habitat are infrequent and fragmented for many rare species characteristic in areas of low productivity as a result of surrounding agricultural land. It is unlikely, therefore, that many of the species in these areas will be able to migrate naturally, even though climatic changes may increase their vigour and reproductive capability.

Velichko et al. (1990) review estimates of migration rates for a number of northern species and suggest that for the thermophilic species (generally favoured by suggested climate change), the expected rates of migration will be between 100-200 m/year. In Britain during the Holocene, tree-species migration reached 700 m/year with minimal dispersal distances up to 10 km per generation (Birks, 1989). In the current context of scenarios of rapid climatic changes, rates of migration of up to figures 80 km/year would be required and only invasive weed species with short generation time and large dispersal distances may be able to achieve this rate.

In the rainforests of Veracruz, for at least two species ***Trichilia martiana*** and ***Dendropanax arboreus,*** most seeds fall within 25 m of the parent tree (Van Dorp, 1985). Obviously, species such as these will be unable to migrate the distances necessitated by changes in climate (approximately 200-300 km) in only a hundred years unless assisted. Even wind-assisted and animal-assisted dispersal may fall short of the mark for many species. For example, for Engelmann spruce ***(Picea engelmannii),*** a tree with light, wind-dispersed seeds, fewer than 5% of seeds travel more than 200 m downwind. This dispersal distance would lead to an estimated migration rate of 1-20 km per century (Seddon, 1971) which reconciles well with rates derived from fossil evidence for trees of between 10 and 45 km per century (Davis and Zabinski, 1990; Roberts, 1989).

3.1 Global overview

Several authors (eg Emanuel et al., 1985a, 1985b; Shugart et al., 1986; Sargent, 1988; Solomon, 1989; Rizzo and Wiken, 1989) have examined potential broad-scale impacts of climate change on major vegetation types using a direct transfer function approach. These analyses show that based on the relationships between climate and vegetation zones, significant changes are possible under the suggested climate change scenarios. It is important to remember when interpreting these types of analyses that the areas defined as decreases or losses are actually vegetation zones and geography which, as a result of the changed climate, no longer have a climate which is considered optimum for the current vegetation type. These areas, therefore, are those which would be most vulnerable to disruption as a result of the projected climatic changes. As such, considerable care should be given to development of management strategies for these areas (eg establishment of biosphere reserves).

The Holdridge Life-Zone Classification system (Holdridge, 1964) has been used by a number of authors to analyse the impacts of a changing climate on global vegetation distribution. These analyses assume that the variance in geography of climate controls is equal to the variance in geography of vegetation. It should be noted that the estimate of changes in global forests especially in tropical forests, are quite sensitive to scenarios and forest models used. Moreover, the rate at which changes in actual species ranges will occur is not estimated.

Emanuel et al. (1985a, 1985b) modified the Holdridge Life-Zone Classification based on current climate by introducing temperature changes (without precipitation or CO_2 changes) as projected by the Geophysical Fluid Dynamics Laboratory (GFDL, 1980 version) scenario. This analysis showed the following impacts on the global ecosystems:

- global forest area decreases by 6%;
- the world's grasslands increase by 25% and deserts by 7%;
- the largest areal changes occur in polar latitudes with a 37% decrease in boreal forest and a 32% decrease in tundra;
- the boreal forest zone shifts poleward to replace about 42% of the tundra and the tundra itself shifts further poleward;
- some of the former boreal forest zone is replaced with other forest types (eg cool temperate or boreal moist forest) or by shrublands (eg cool temperate steppe);
- in temperate regions, forest types change from wetter to drier types; and
- in the tropics, subtropical forest areas decrease by 22% while subtropical thorn woodland and subtropical desert areas increase by 37% and 26% respectively and tropical forest areas increase by 28%.

In an alternative approach using stand simulation modelling, Solomon (1986) reported that when precipitation as well as temperature changes derived from the GFDL (1980) model were incorporated, changes to forest and tundra in eastern North America were qualitatively similar to the results of Emanuel et al. (1985b) above; except that forests in the temperate zone decreased, resulting in a net decline in forest biomass in eastern North America. Solomon's findings are consistent with those based on other modelling and palaeo-based studies reported by the US EPA (1990). The EPA studies also conclude that forests in the western US might become progressively more xeric in composition, with a resulting biomass reduction of about 40%.

A subsequent analysis (Leemans, 1989), using both temperature and precipitation scenarios to define life zone changes, examined the impacts of climate change on 12 vegetation zones (Holdridge life zones combined into 12 vegetation zones) which were developed to correspond roughly to the vegetation classification of Udvardy (1975). Under the 2 x CO_2 climate scenario the following changes in vegetation distribution patterns were observed (see Figure 3.1):

- greatest vegetation losses were seen in high latitudes, where the amount of land classified as polar deserts, tundra and boreal forest decline by about 7 million square kilometres (20%);
- the greatest increases are experienced in the warm savannas primarily from losses of subtropical forests, warm desert and tropical rainforest in that order;
- of the 57 million square kilometres classified as closed forest life zones under the current climate, 35% are projected to be located in regions in which will become inappropriate; and

- losses of areas conducive to closed forest are approximately balanced by new areas which could support closed forests.

These analyses indicate that tropical forests also appear to be susceptible to climate change (Solomon, 1989). Since tropical species have evolved in areas where seasonal variations in rainfall and temperature are slight, they generally have very narrowly prescribed physiological requirements. Solomon (1989) found that certain critical areas of the tropical forest that today cover Central Africa and Brazil would die back as a result of changes in the amount and annual distribution of available water. Other factors that need to be considered are that the accelerated decomposition of organics in the soil as a result of higher temperatures (see Working Group I Report, Ecosystems) and accelerated erosion in these areas will also hamper the migration of tropical species.

An important factor in the response of tropical forests is the current domination of land use considerations over those of the natural ecosystems. The ability of tropical forests to take advantage of expanded climatic ranges would be severely curtailed by human demands in these regions for land and fuelwood. Although this interaction is also prevalent in other regions, development pressures in those areas in and around tropical forests are, and will be, particularly acute.

These proposed changes can be put into perspective by examining the relative surface area and net primary productivity of various vegetation zones.

3.2 Specific vegetation zones

3.2.1 Boreal and tundra

Sargent (1988) used GFDL-based climate-change scenarios (1980) to examine the possible climate response of the Canadian Boreal forest zone to a doubling of CO_2. The procedure for identifying environmental limits as proposed by Box (1981) was used to define and model the response of, the domain of the Boreal forest zone. This analysis suggests that under the 2 X CO_2 climate scenario, the area climatically suitable for non-transitional boreal forest would suitable for boreal forest in northern Canada is approximately 70 million hectares versus a loss on the southern margin of approximately 170 million hectares.

The impacts of a 1°C and a 2°C increase in mean annual global temperature on boreal and tundra ecosystems can also be examined through palaeoreconstruction techniques. Velichko et al. (1990) suggest that the warming of 1°C by the turn of the century corresponds to that experienced during the optimum of the Holocene (5000-6000 years bp) and a warming of 2°C (by the 2020s) corresponds to that experienced during the Mikulino (Eemian, Sangamon) Interglacial (approximately 125,000 years bp). Based on these reconstructions, the climatic zones which currently support particular vegetation types in the USSR and North America could shift in the following manner (based on equilibrium models):

(i) Global warming of 2°C

Both coniferous and broadleaved thermophilic tree species may find favourable environments much further north than their current limits. In the northern parts of the Asian USSR the boundary of the climatic zone currently associated with the taiga could move northward 4°-5° of latitude (500-600 km). That associated with the tundra could disappear from the north of Eurasia.

Projected changes in precipitation may allow some species to expand their boundaries southward. As a result, broadleaved species range may expand and these ecosystems may be more maritime in terms of species composition. The climatic zone associated with the forest steppe in the European USSR will move southward 500-600 km and could occupy most of the steppe zone. In the southern portions of western Siberia the forest-steppe boundary could move up to 200 km.

(ii) Global warming of 1 °C

Impacts on the climatic zones associated with current vegetation cover relative to the present situation are similar to those described above, except smaller in amplitude. That associated with the current tundra zone is expected to become significantly narrower than at present.

These palaeogeographical reconstructions cannot be used as direct analogs of the expected impacts on natural terrestrial ecosystems at the beginning and middle of the 21st century, since they represent a quasi-stationary state and occurred in the absence of the prior CO_2 concentration increase, which itself is likely to have profound effects. To achieve this state will take at least several centuries. The probable non-equilibrium response at the turn of the century and the middle of the 2020s is suggested by the analysis of several meridional transects conducted by Velichko et al. (1990). Discussed here are a north-east Europe transect (50°E) and a North American transect (100°W).

Under global warming of 2°C shifts in the associated climatic zonal boundaries are approximately 550 km for coniferous broadleaved forests and 220 km for coniferous forests (Figure 3.2). Under an increase of 1°C in global mean temperature, expected shifts of boundaries are less significant. Coniferous forest would almost reach the coast. This will not happen, however, primarily because of the time limitation at the rates of migration of the existing tree species. Actual shifts in the areas inhabited by these tree species are suggested to be no more than 10 km. It will be only birch ***(betula spp.)*** (pioneer species) that will be able to expand its range by 1 km/year.

Warming will increase the competitiveness of oak and other broadleaved species and they will become more abundant. By the beginning of the century, however, this may be evident only in the composition of the undergrowth. At the same time, one can expect higher numbers of pioneer species (eg birch) since the cold-resistant tree species will probably have lower tolerance against diseases and pests and thus will suffer losses in their numbers as climate warms.

Along the North American transect (Figure 3.3) potential shifts in the zonal boundaries could be 2.5° of latitude under a 1°C increase in mean global temperature and approximately 5° of latitude under a 2°C warming. Unlike Eurasia, the tundra zone may remain in North America under the suggested climate change. In reality, the shifts in the ranges of tree species and ecosystems could reach only several kilometres. Even elm, with its high seed dispersal capabilities, may not be able to advance beyond its current boundaries by more than 5 km by the turn of the century and 17 km by the middle of the 2020s.

If the proposed GHG-induced warming occurs, species shifts similar to those in the Pleistocene would occur, and climatic zones would move hundreds of kilometres toward the poles (Davis and Zabinski, 1990; Frye, 1983; Peters and Darling, 1985). A 300-km shift in the temperate climate zone is a reasonable minimum estimate for a 3°C warming, based on the positions of vegetation zones during analogous warm periods in the past (Dorf, 1976; Furley et al., 1983). Vegetation would take decades to follow these zonal changes. With a poleward shift of forests, bird and mammal populations unique to the tundra will decline and/or be replaced by those from lower latitudes, thereby experiencing a significant reduction in their ranges of the tundra species (Lester and Myers, 1989). It has also been suggested that tundra nesting habitat for migratory shore birds might be reduced by high arctic warming (Myers, 1988).

Additional support that vegetation boundary shifts of this magnitude or greater may occur comes from estimating ecological requirements of some species. For example, the forest industry is concerned about the future of commercially valuable species, such as the loblolly pine ***(Pinus taeda).*** This species is limited on its southern border by moisture stress on seedlings. Based on its physiological requirements for temperature and moisture, Miller et al. (1987) projected that the southern range limit of the species would shift approximately 350 kilometres northward in response to a global warming of 3°C.

Davis and Zabinski (1990) have projected possible northward range movements among several North American tree species, including sugar maple ***(Acer saccharum)*** and beech ***(Fagus grandifolia),*** from 600 kilometres to as much as 2000 kilometres in response to the warming caused by a doubled $C0_2$ concentration. Beech would be the most responsive, withdrawing from its present southern extent along the Gulf Coast, and retreating into Canada. Changes in species composition of forest stands in Poland during the past two centuries have shown a close correspondence with climate shifts. Based on climate-vegetation associations, suggested GHG-induced changes in climate will favour the succession of broadleaf species and increase the stresses on needle-tree species (Kowalski, 1989).

Kauppi and Posch (1985), using calculated temperature sums to define the current boreal zone in Finland, recalculated these sums based on temperature data from the Goddard Institute for Space Studies (GISS) scenario and suggested the possible effects on forestry resources within Finland. Their analysis indicates that the defined boreal zone domain will be displaced northward by 500-1000 km by the suggested climatic warming.

Forest production in Sweden is projected to increase as a result of a 3°C increase in mean annual temperature (Boer et al., 1990). For pine, projected increases in production range from 16-43% with the largest values expected in the mid-latitudes of Sweden. In general, the greatest forest growth changes within the boreal forest zone of Fennoscandia are expected to occur in the northern maritime regions.

Many forest stands in the boreal zone and in alpine regions were formed hundreds of years ago under climate regimes different from those of today. They can tolerate today's climate even though it may not optimal for regeneration and growth. Changes in climate on top of these less-than-optimal conditions could adversely affect these forest stands as both the direct effects of the changed climate on growth and

Table 3.1 Current relative surface area and net primary productivity of various vegetation zones

Vegetation zone	Surface area (%)	Annual production (%)	Relative productivity (1000 tonnes/km²)
Forests	21.0	36.6	1.6
Temperate woodlands	1.3	2.3	1.5
Chaparral, maquis, brush	1.7	1.5	0.8
Savanna	15.1	29.6	1.7
Temperate grasslands	8.4	7.3	0.8
Tundra Arctic/alpine	6.4	1.6	0.2
Desert and semi-desert scrub	14.1	2.3	0.1
Extreme desert	6.0	0.1	0.01
Perpetual ice	10.4	0.0	0.0
Lakes and streams	1.3	0.6	0.4
Swamps and marshes	1.3	5.5	3.6
Bogs	1.0	1.1	1.0
Cultivated land	10.7	11.3	0.9
Human area	1.3	0.3	0.2

reproduction and the indirect effects such as potential increases in fire and pests and pathogens, come into play.

The regeneration phase of forests is probably the most sensitive part of the cycle and where effects of climate change may be felt first. Some impacts on forests due to changes in climate will be positive (eg suggested increases in growth rate and range) for some species in some areas. The actual impact, however, will depend on the combined effects of changes in the climate and related ecosystem as well as pressures from outside of the ecosystem (eg anthropogenic). The fact that there is a wide range of ages of forest stands over the landscape could provide a degree of resilience to the landscape since sensitivity to change will probably vary with stand age.

A possible ecological consequence of the projected increased thermic oceanicity in western Norway is that frost-sensitive species will expand considerably eastward along the fiords, and upwards (Holten, 1989). Owing to the projected higher summer temperatures, the vertical vegetation zones in south Norway could move 200-300 m upwards in the fiord district and possibly 300-400 m in the continental parts of southern Norway.

A poleward shift of fish and marine mammal populations are likely owing to shifts in warm ocean currents (Dunbar, 1955). Harington (1986) speculates on the fates of several species from changing climate in the Canadian Arctic. Harp seals (*Phoca groenlandica*), harbour seals (*P. vitulina*), white whales (*Delphinapterus leucas*) and bowhead whales (*Balaena mysticetus*) would spread further north and increase in numbers. In contrast, ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) would shift further north into the coldest water and shrink in number and range.

Arctic mammals and birds which use sea-related biological communities as a food source and also as a substrate will be impacted by projected climatic changes. For example, changes in the abundance and location of polynyas and leads may adversely impact on many arctic mammals and birds, including whale populations. Polar bears use ice for travelling and feeding with their range determined by the maximum seasonal extent of sea ice in any one year. Although adaptable, loss of sea ice and ice seals would place the survival of polar bears at risk. Walruses' (*Odobenus rosmarus*) responses to climatic changes are more complex. Because of their wider ranges of habitat and food they would appear to be less susceptible to adverse impacts. On the other hand, reduced ice cover would leave walruses more vulnerable to hunting pressures and would allow other species such as the sea otter to extend their ranges northward increasing competition pressures.

3.2.2 Montane and alpine

Busby (1988) examined the geographical implications of climate change for alpine vegetation in Australia. The present alpine vegetation is restricted to disjunct mountain tops and high plateaux in southeastern Australia. According to this analysis, the climatic areas capable of supporting the current alpine vegetation will retreat to a very small number of isolated mountain peaks, thereby threatening the survival of the majority of the present alpine species. Similar results were also suggested for a number of alpine species in the Alps and East African mountains. In Mexico, Menchaca and Byrne (1990) hypothesise that a 2°C increase in temperature could increase the vulnerability of extinction of disjunct populations near the summits of isolated mountain ranges.

Since mountain peaks are smaller than bases, as species shift upward in response to warming, they typically occupy smaller and smaller areas, have smaller populations, and may thus become more vulnerable to genetic and environmental pressures (Korner, 1989; Murphy and Weiss, 1990). Species originally situated near mountain tops might have no habitat to move up to, and may be entirely replaced by the relatively thermophilous species moving up from below. Examples of past extinctions attributed to upward shifting include alpine plants once living on mountains in Central and South America, where vegetation zones have shifted upward by 1000-1500 m since the last glacial maximum (Flenley, 1979; Heusser, 1974).

In Mexico, the potentially most vulnerable ecosystems are the high elevation alpine grasslands or 'Paramo' (Menchaca and Byrne, 1990). This vegetation type is currently restricted to the highest volcanic peaks (elevations > 4000 m). A vertical shift of 200 m (ie temperature increase of ca 2°C) would be sufficient to reduce drastically the extent of the paramo, and in some cases may even result in local extinctions.

Migration of wildlife in more heavily populated alpine regions such as the Alps could become more restricted since a more favourable climate would expand the area of land claimed for agriculture to include that at higher elevation (Eybergen, 1989). Some bird species which currently find a niche in the alpine climate areas may face more competition and be more vulnerable to predation as other species migrate upwards unless they can also shift upwards.

One of the long-term impacts of climatic changes in montane and alpine regions is the potential for speciation. As populations which have moved upward become disjunct, environmental and other pressures may lead to the creation of new species. This process would, however, require many generations.

3.2.3 Temperate

In Norway (Holten, 1990b), the alpine region will have a marked retreat from the current 30% of the total land area, to 7%. On the mountain plateau, Hardangervidda in southern Norway, Finmarksvidda in northern Norway, middle boreal coniferous forest is likely to invade, mainly Norway spruce ***(Picea abies)*** and Scots pine ***(Pinus sylvestries),*** possibly with severe consequences for the reindeer stock.

The impact of climatic change on the present temperate rainforest is uncertain. For example, almost all of Tasmania is expected to become, at best, climatically 'marginal' in terms of temperate rainforests (Busby, 1988), largely due to a rise in winter temperatures suggested by climate scenarios. This increase in temperature is unlikely to have a significant direct effect on the forest, but may facilitate the invasion of less frost-tolerant species.

In Australia, the Mediterranean-type ecosystem is at the southern edge of the continent. As the biota cannot migrate south, this is one of the biomes where under the projected climatic changes, significant adverse changes and loss of species would occur (Australian Government Publication, 1989).

Forest and grassland productivity in temperate regions of Australia may increase, under the influence of GHG-induced global warming, as may the number of rodents and their predators. Species limited by wet, cold conditions may increase where the climate becomes drier or warmer. With specific reference to New Zealand, Keys (1989) suggests that a number of introduced species of insects and fish could spread to higher latitudes with warmer temperatures, and rabbit problem areas could expand in eastern New Zealand.

Manabe and Wetherald (1987) and Kellogg and Schware (1981), inferred from precipitation patterns ascribed to past warming periods, that substantial decreases over North America's Great Plains are possible - perhaps being as much as 40% by the early decades of the next century.

Forest simulation models and ecological response surfaces have been employed to examine the possible effects of global change on temperate forest ecosystems. Forest decline, possibly within 30-80 years, and mortality is suggested for southeastern, northeastern and Lake states regions of the US.

With declining forests, the incidence of disease, fire and insects may be exacerbated and large-scale forestation will be needed to ameliorate the potential negative impacts (quality of biotic habitat, water quality and quantity, soil erosion, and recreation opportunities.

Temperate forests are likely to increase in Scandinavia; Norway (Holton, 1990b) could experience an increase in the temperate forest area, mainly oak ***(Quercus robur)*** and beech ***(Fagus sylvatica)*** from current 0.7% to 13%, thus being a significant new vegetation type in most areas.

Projected increases in winter temperatures could lead to a reduction in the range of many perennial woody species of the temperate zone. Forested areas which currently support vigorous growth of such species as white spruce, Douglas fir, Norway spruce and Scots pine, may become too warm in the winter months to satisfy their chilling requirements (Lavender, 1987) and will eventually no longer be part of the species' ranges (see Working Group I Report, Ecosystems).

Climatic warming may bring about early budburst, for some species, increasing the length of the growing season with possible positive ramifications for productivity. Earlier budburst, however, could lead to increased risk of frost damage (although the possibility of late spring frosts is expected to be reduced with warmer conditions) and thus would have negative impacts on productivity.

3.2.4 Semi-arid and arid

The response of semi-arid and arid regions of the world is also uncertain at this time. The large-scale vegetation models mentioned above give some indication of the possible changes in these regions; however, the uncertainty associated with the impact of climate change on the monsoon wind systems of Africa, Asia and Australia, and the vital role climate variability plays in developing and maintaining these regions makes it difficult to provide any plausibility to semi-arid and arid ecosystems scenarios.

Graetz et al. (1988) looked at the impacts of climate change on ecosystems of arid Australia and found that vegetation changes were primarily influenced by changes in available plant moisture and only secondarily by temperature. This was reflected by an increase in the areal coverage of trees and shrubs in those areas where precipitation is suggested to increase and a decline in those areas where precipitation decreases. This pattern was modified somewhat by temperature since, in the model used, a 20% increase in precipitation was compensated for by a temperature increase of 3°-4°C (ie a net decrease in available moisture). Owing to the effect of elevated CO_2 on increased water efficiency, the large increase in CO_2 concentrations is expected to have a particularly profound impact on water-limited vegetation.

In the semi-arid, arid and hyper-arid ecoclimatic zones of the Mediterranean, analyses suggest that GHG-induced climate change will reduce plant productivity and result in desertification of the North African and Near Eastern steppes (Le Houerou, 1989) due to increased évapotranspiration. The upper limit of the deserts would migrate under the influence of climate change and most likely extend into the area that currently corresponds to the lower limits of the semi-arid zone (ie foothills of the High, Mid and Tell Atlas and Tunisian Dorsal in Northern Africa and of the main mountain ranges of the Near-Middle East - Taurus, Lebanon, Alaoui, Kurdistan, Zagros, and Alborz).

Bryson (1973) suggests that Sahelian drought may be due to changes in the world distribution of temperature consequent upon an increase in the concentration of atmospheric GHG. He calculated the increase of temperature at the earth's surface as a result of an increase in CO_2 to be of the order of 0.1°C since 1940 and showed this as being capable of displacing the latitude of the subtropical high pressure zone over the Sahara equatorward by 15 km. A rise in global temperature of the magnitude envisaged over the next 10-50 years could lead to a greater equatorward penetration of the aridity influence of the Sahara desert and consequently equatorward displacement of the vegetation belts in West Africa.

4 Changes within ecosystems

Projected climatic changes will have impacts on the different components and processes within ecosystems. These factors, which may be additive with the direct effects of climatic change, include changes in soil processes, hydrology, disturbance variables (eg fire, and soil and surface instability), pests and pathogens, and competition. In some cases, ecosystems will be more sensitive to changes in these factors than directly to changes in climate.

4.1 Water balances in terrestrial ecosystems

Suggested GHG-induced climatic change will profoundly affect hydrologie relationships in natural terrestrial ecosystems, both directly by altering inputs of precipitation, runoff, soil moisture, snow cover, snowmelt and évapotranspiration outputs, as well as indirectly by transforming sea and lake levels, which influence water levels in coastal and shoreline ecosystems. Significant increases in évapotranspiration could reduce soil moisture and have adverse effects on forests. Even small alterations in the annual pattern of hydrological fluctuations may have dramatic impacts. For example, work by Kushlan (1986) in the Florida Everglades has demonstrated that subtle changes in hydrology have profound effects on population stability of wading birds, which in turn may affect energy flow and ecosystem functioning. Artificial drainage of bogs has shown that minor changes in hydrology have a marked impact on bog vegetation. Sphagnum species with their key role in the accumulative processes in bogs appear very sensitive. Bottomland hardwood forests in the southern US are susceptible to changes in duration, timing and depth of inundation (Teskey and Hinkley, 1977; DeLaune, 1987). Certain species of wetland plants need a period of low water in order to allow reproduction (Markham, 1982). A change in the seasonality of precipitation could adversely affect such species.

The seasonality of rainfall also affects its impact. A lengthening of the dry season, or conversely an increase in groundwater table levels, could both accentuate salinisation problems. In Mediterranean and semi-arid climates, where évapotranspiration exceeds precipitation for long periods and increased percolation from vegetation clearing or excessive irrigation may have raised the water table, surface soil salinisation can be a major problem. Such salinisation can kill all but the most halophytic vegetation, increase soil erosion and reduce water quality. Salinisation is already a problem in many Mediterranean and semi-arid regions (eg coastal Western Australia, the Mediterranean, subtropical Africa), and is a major cause of increased desertification. This is particularly common in parts of the Southern Hemisphere where forests have been cleared for rangeland or agriculture.

Relatively small changes in precipitation regimes may have major impacts on runoff, especially in arid and semi-arid areas. Seasonal floodplains of tropical areas (eg the Pantanel of Brazil, the Inner Niger Delta in West Africa, the Okavango Swamp of Botswana, and the Grand Lac of the Lower Mekong) all provide large areas of important wetland habitat. Such areas are subject to sedimentation (Maltby, 1986). They could be further altered by any change in sediment inputs caused, for example, by increased intensity or duration of precipitation events.

There is a number of secondary impacts to be considered. For example, if agricultural areas become drier and hotter during the summer growing season, the demand for water for irrigation may have negative effects on wetlands, either through direct losses or indirectly through lowering of local and regional groundwater tables. In addition, there is evidence for concern over the potential for increased impacts from acid deposition and other forms of pollution as water tables are drawn down in wetland areas (van Dam, 1988).

Increased surface water flooding, either from melting permafrost, or from increased precipitation and surface runoff in lower latitudes, can cause catastrophic effects in vegetation not adapted to surviving low soil oxygen levels. In California, for example, spring runoff is predicted to increase as a result of earlier snowmelt from the Sierra Nevada, induced by higher temperatures (Gleick, 1987). Forest and shrub stands not normally subjected to flooding can be killed within weeks if subjected to prolonged surface flooding. Even a below ground rise in the water table can kill sensitive species. Lowland ***(Podocarpus)*** forests on the west coast of the south island of New Zealand, for example, are particularly vulnerable to this phenomenon (NZ climate impact document, 1989).

The functioning of wetlands will be affected by the proposed GHG-induced climate change. For example, decomposition in wetlands appears tied closely to temperature (Brinson et al., 1981). Generally it may be expected that the results of climatic change will invoke substantial variations in the fluxes from wetland areas. Sediment output, methane production, denitrification and similar fluxes will be affected. Predicting precise effects is difficult, particularly since there will be a period of transition during which fluxes will be somewhat variable. A drawdown of water levels in wetlands would permit the exposure of wetland sediment and increase aerobic activity. In addition to the oxidation of organic matter, this could permit the export of sequestered nutrients, at least in the short term. Although it is not clear if wetlands more effect or reflect hydrology, regional hydrologic relationships involving wetlands would be altered, potentially reducing quality and quantity of water supplies.

It is an axiom that biological productivity increases with increasing temperatures (to a certain threshold) in some species and declines with increasing temperature in others. For example, the productivity of ***Phragmites communis*** (reed) has been shown to vary directly with summer warmth (Spence, 1964). However, the productivity of many wetlands is nutrient-limited or limited by the water regime. Wetlands in continental climates may undergo large variations from year to year in their productivity largely owing to water availability. For example, over a five-year period, Van der Valk and Davis (1978) found an 18-fold difference in primary productivity in a prairie marsh in the United States due to water level changes. Increased salinisation of wetlands in more arid areas, or the concentration of other toxics, may result from increased rates of évapotranspiration, thereby adversely affecting productivity.

Wetlands along inland lake shores are a somewhat special case, being dependent upon lake levels. They provide many of the same benefits as do coastal wetlands. Certainly, should water levels rise or the seasonal cycle of lake levels change, similar impacts to those anticipated for coastal wetlands may be expected. However, it is suggested that in many lakes one impact of climate change may be to change mean, maximum and minimum levels, and seasonal patterns of lake levels (Cohen, 1986; Croley and Hartmann, 1989). Unsuitable substrates or bathymetry may limit wetland adaptation to lower water levels as well. In the Great Lakes of North America, modelling of different scenarios of falling water levels suggests major impacts on shoreline wetlands (Kolasa et al., 1988).

With a warming climate at higher latitudes, some lakes supporting large fisheries could be desiccated, large areas of permafrost would melt, increasing turbidity and organic loading in streams and lakes and the arctic pack ice would recede northward, thereby affecting the fisheries and the food chains supporting them. Climatic warming in the worst case could initiate a complex series of migrations and extinctions of fish species over broad inland areas. At a minimum it could alter the present pattern of species abundance. Compensatory effects such as the possible northward extension of the ranges of other species may be slow because freshwater habitats are not always continuous. Ecosystem adjustment to a climatic warming may be rapid in the lower trophic levels, but negative impacts are likely to occur for decades in fish communities before positive adjustments are realised (Hecky, 1987).

Gorham (1988) suggests that climatic warming may threaten severe biotic impoverishment of northern peatlands. In areas of permafrost, melting may lead to substantial drawdown of peatland water tables and increased oxidation. Similarly, further south, peatlands may be subject to drying. The net effect would be an increase in CO_2 emissions, for all northern peatlands perhaps equivalent to 18% of the carbon released by fossil fuel consumption. These impacts may be offset since lowering water tables would most likely reduce emissions of methane, and thermokarst erosion could lead to renewed peat accumulation (although peatlands do tend to be thermally conservative (Roulet, 1989)). Moreover, with climatic warming, more northern peatlands may become more active, sequestering carbon from CO_2 but releasing methane (Morrissey et al., 1988). The net effect remains uncertain.

Changes in the water balance in peatlands towards less lateral and vertical outflow can increase concentration of nutrients and other minerals. This in turn would affect species composition and succession of ombrotrophic wetlands by promoting the growth of species characteristic of more eutrophic environments (van Dam, 1989).

For some peatlands with a critical water balance, reduced water tables will result in shrinking and mineralisation of the peat with a consequent alteration of drainage patterns and species composition. Changes in climate would likely affect the process of paludification. Certainly, drier environments would inhibit the initiation of peat growth (although, with lesser impacts on existing peatlands (Roulet, 1989)). In areas where bogs are already degrading, the results could be quite severe.

4.2 Ecological interactions

The suggested changes in climate may induce a change in the structure and composition of natural terrestrial ecosystems. The actual impact depends on a number of factors including the response of major components of the ecosystem, level of competition, relative location of potential immigrants and human interference. The interplay of these factors could lead to one or more of the following scenarios:

- One of the dominant species is unable to survive under the new climate, disappears and is replaced by more thermophilic members of the same community. An example is the spruce broadleaved forest of eastern Europe in which the spruce requires temperatures at or below zero for some period of the year. If temperatures rise and these low temperatures no longer occur, spruce would disappear from eastern Europe over a period of 50 to 100 years and be replaced by broadleaved forests.

- The main dominant is unable to survive, disappears and is replaced by rapidly spreading pioneer species (eg birch and aspen) initially, and thermophilic immigrants eventually. Duration of this process depends on how far these potential immigrants must disperse and on their rates of dispersal.

- Climatic change is supportive for less dominant species and the dominant species is unable to oppose the immigration of more competitive species. This scenario is indicative of the process of the advance of forests into areas previously occupied by tundra and steppe.

Given the new associations of species that could occur as climate changes, many species will face 'exotic' competitors for the first time. Local extinctions may occur if climate change causes increased frequencies of droughts and fires, which favours invading species. One species that might spread, given such conditions, is ***Melaleuca quinquenervia, &*** bamboo-like Australian plant. This species has already invaded the Florida Everglades, forming dense monotypic stands where drainage and frequent fires have dried the natural marsh community (Courtenay, 1978; Myers, 1983).

Annual exotic weeds, particularly at the edge of species ranges, are likely to be favoured in competition with woody perennials within ecosystems under the effects of a changing climate. The favouring of annual exotics, however, will be further enhanced by (i) the increased mortality of natives, creating gaps for colonisation of sun-loving annuals; and (ii) the relative lack of native herbivores, which already gives exotics an advantage. In general, exotic species have been shown to thrive in disturbed landscapes (Orians, 1986). The myriad sources of disturbance to landscapes (fire, climatic intolerance, erosion and soil slip etc) will create enhanced opportunities for colonisation by exotic weeds. Migration of weedy species may also be enhanced by human land use. For example, areas along corridors formed by roads, railways etc, and in open ground created by human disturbances, promote the growth and spread of weedy species, including aliens which are fast growing and fecund.

Soil moisture is a critical factor in mediating competitive interactions among plants, as is the case where the dog's mercury ***(Mercurialis perennis)*** excludes oxlip ***{Primula elatior)*** from dry sites (Ford, 1982). Decreased soil moisture could adversely effect existing plant species, reducing their vigour and competitive capabilities. This could allow more aggressive and less moisture-demanding plants to move into the affected areas. In addition to annual grasses and forbs, another category of exotic that is likely to increase is symbiotic nitrogen-fixing shrubs. These have an enhanced ability to colonise relatively bare ground, and to arrest further succession for some decades (eg Vitousek, 1986; Braithwaite et al., 1989).

A reduction in precipitation as is projected for some regions can change the floristic composition of the affected ecosystems. Diarra (1988) examined the changes in ***vetiveria nigritiana*** and ***eragrostic bareri*** grasslands in the Niger floodplain, Central Mali, as affected by prolonged periods of reduced rainfall. Diarra reported that a major change in the plant composition of the Niger floodplain grasslands followed the drought of 1980-86. Perrenials that previously dominated the eragrostic grassland ***(eragrostis barteri)*** gave way to annual species (eg ***panicum subalbidum, Seteria pallidetuska*** and ***borreria choetociphala).*** He also found that the vetiveria grassland which in the pre-drought period was dominated by tussock grasses (including ***vetiveria nigritiana*** and ***sorghum trichopus)*** was in the post-drought period invaded by annual grass species.

4.3 Biological diversity and endangered species

The loss of biological diversity is increasingly being recognised as one of the most critical environmental issues of the 1990s. Estimates of the annual global rate of species extinction range from 1000 to 10,000 times that before human intervention. The basic issue that drives all concerned about biological diversity is the accelerated and irreplaceable loss of genetic material, species, population and ecosystems. Associated with this loss is the loss of products obtained from nature (presently and potentially), possible disruption of essential ecological processes and service, and loss of options for biological and cultural adaptation to an uncertain future.

Natural terrestrial ecosystems such as forests and lakes are a rich source of global biological diversity. Forests include herbaceous plants, bryophytes, hepatophytes, algae, fungi, protists, bacteria and many groups of vertebrates and invertebrates, as well as tree species. In addition to this 'compositional' or taxonomic diversity, these ecosystems also can be characterised in terms of structural (physical habitat) and functional (ecological and evolutionary) diversity.

Much of the current discussion on loss of biological diversity is centred on the destruction of tropical forests and the subsequent conversion to agricultural land. The greatest concentration of species diversity in the world is found in tropical rainforests. These forests account for only 7% of the land area, yet contain at least 50% of all species. Current estimates indicate that annually, approximately 1% of this biome is being deforested and another 1% is being degraded.

Temperate and boreal forests are also important sources of global biological diversity. Temperate forest zones have been extensively and uniformly altered by human activity. Most remaining areas are fragmented and highly modified, making those remaining relict areas even more crucial in the maintenance of biological diversity.

Loss of species, particularly those previously identified as being sensitive, will reduce biological diversity. Loss of key species such as primary producers which play a critical role in the support of other species, could begin a domino effect leading to further extinctions and perhaps demise of an ecosystem. Lester and Myers (1989) suggest that if keystone herbivores or their functioning counterparts in other ecosystems become extinct due to global warming, then a chain of extinctions could be set off. As evidence of the importance of key species they report that in the 100 years following the disappearance of elephants in the Hluhluwe Game Reserve in Natal, several species of antelope have been extirpated and populations of open country grazers such as wildebeest and waterbuck have been greatly reduced.

Pain (1988a) describes the potential ecological damage in the Arctic, where sea ice is vital to walruses, seals and polar bears that migrate across it. The ice also supports the arctic food web (algae grows on its undersurface), providing the basis of most arctic food chains. This raises the question of what will happen if the base of the food web disappears with melting ice.

The problems of altered biological diversity are particularly acute for heritage sites and reserves. Optimal management of a worldwide system of heritage sites for maintenance of biological diversity requires a clear understanding of the global pattern and control of diversity and rarity (Soule, 1986; Currie and Paquin, 1987). Optimal management of biological diversity within individual reserves must involve efforts both to maximise and then maintain diversity. Computer algorithms can be used to generate designs that maximise species and habitat diversity in a reserve system (eg Margules et al., 1988) and explicit strategies based on analysis of rare and endangered species distribution patterns (Miller et al., 1987), or synthetic conservation value (Rapoport et al., 1986) can help integrate economic and other constraints into the diversity optimisation process (Schonewald-Cox and Bayless, 1986).

An important result for design of heritage areas with maximal diversity is the discovery that inclusion of environmental variability in classical demographic models drastically reduces population persistence times. Consequently, extremely large population sizes may be necessary to confer long persistence times on populations (Soule 1987). Modelling of extinction in relation to body size, population size, and reserve area (Belowsky, in Soule, 1987) indicates that large-bodied animals require smaller population sizes but larger reserve areas than small-bodied animals. Belowsky concludes that present reserve sizes are adequate for persistence of some large herbivores, but no large carnivores, for up to 1000 years.

One of the most ominous results in light of global climatic change comes from the modelling of catastrophes and demographic minimum viable population sizes by Evens et al. (in Soule, 1987). Median extinction times were dependent on the logarithm of the initial population size and largely insensitive to initial population size (ie very large initial sizes are required to substantially lengthen persistence times). Shaffer (in Soule, 1987) provides a startling synthesis of these results and emphasises that the size and number of current reserves are inadequate for long-term protection of some large and rare animals.

The message is that species with high variance in population growth rate require very large reserves or intermittent human intervention to reduce the variance in growth rate (especially the tendency to low growth rates).

Not surprisingly, there are different predictions from various experts concerning the impacts on migratory birds. Some believe that migratory birds may, in general, expand their ranges, and breeding success may increase owing to warmer temperatures, although sea-level rise will further diminish the essential coastal flyway marshes which are already threatened by shoreline development (Breckenridge, 1988; Harington, 1986). Other researchers, however, suspect that the impacts on bird population could be calamitous, as finely calibrated hatching and nurturing patterns may no longer be synchronised. For example, the emergence of young must be closely timed with the availability of food (Lester and Myers, 1989; Pain, 1988b). Disruption of feeding patterns could affect survival of the next generation (Topping and Bond, 1988). The US Fish and Wildlife Service (1988) foresees losses among Arctic nesting shore birds, due to disruption of hatching which is currently timed to the availability of food, but notes the possibility of population gains for nesting geese and seabirds responding to more favourable temperatures and increases in their food.

4.4 Pests and pathogens

Some pests and pathogens are likely to increase their ranges as a result of the projected changes in climate and, in the case of insects, increase their population densities. This could place at risk the health of ecosystems and thereby play an important role in determining future vegetation (Winget, 1988) and animal distributions. As warmer temperatures enable the invasion of tropical pests and pathogens into higher latitudes, mid-latitude hosts may be exposed for the first time to many tropical pathogens with which they have had no previous evolutionary history, and hence no opportunity to develop resistance. With the expansion in the range of insects or rodents, the range of associated disease-causing viruses and bacteria may expand (Liehne, 1988; Miller, 1989).

Locusts and moths are more active in warmer climates and could have further deleterious effects on natural vegetation. Temperature is the most important climatic factor controlling mountain pine beetle populations (Safranyik, 1981) with proposed milder winters having less of a devastating effect on over-wintering larvae. GHG-induced climate change will allow these populations to extend their range to higher latitudes and increase the hazard in areas currently experiencing outbreaks of the mountain pine beetle. Population dynamics of spruce budworm are also influenced by climate (Ives, 1974; Wellington et al., 1950; Greenbank, 1956) with temperature being the dominant climate factor.

Since wetlands, particularly seasonal wetlands in warmer regions, provide habitat for the breeding and growth of vectors of a number of serious diseases such as malaria, filariasis and schistosomiasis (Gopal, 1988), an increase in average temperature or any change in the distribution of seasonal wetlands will alter the temporal and spatial distribution of these diseases. Increases in rainfall and temperature in tropical regions of Australia could increase receptivity and hence vulnerability to malaria, increase the incidence of epidemic polyarthritis, and extend the geographical area of endemicity of Murray Valley encephalitis virus and possibly the frequency of Australian encephalitis outbreaks, particularly at the southern boundary of the monsoonal influence (Liehne, 1988).

Health threats to wildlife may also occur under different climates. The spores of the botulism bacterium ***(Clostridium botulinum)*** occurs naturally in soils and mud. Increasing temperatures along with low concentrations of oxygen favour the growth of the organism and production of toxin. Their development is clearly tied to warm, dry weather and degradation of wetlands by eutrophication, conditions which may be enhanced by climate change. This would be detrimental for wildfowl and other susceptible populations in northern and prairie wetlands.

Pest outbreaks may result because of the increased stress and mortality of standing vegetation resulting from a combination of climate-driven stressors. An example from New Zealand concerns hard beech ***(Nothofagus truncatd).*** A 3°C rise in temperature would increase annual respiratory carbon losses by 30%; such a loss exceeds the total annual amount allocated to stem and branch growth for this species (Benecke and Evans, 1987). With insufficient reserves to replace current tissue, the tree is weakened, and becomes more susceptible to pathogens and insects. Following physiological drought episodes, several ***(Nothofagus)*** species succumbed to death from defoliating insects (Hosking and Kershaw, 1985; Hosking and Hutcheson, 1986). A similar insect-induced dieback following two years of drought is currently affecting large areas of mixed conifers in the western Sierra Nevada of North America.

Introduced animals, such as rabbits and foxes in Australia, can have a significant impact on indigenous flora and fauna. The projected climatic changes are likely to favour the introduced species. In Australia, for example, projected increases in rainfall are likely to lead to higher survival rates of introduced species as drought-induced instability is reduced (Main, 1988).

4.5 Disturbance variables

4.5.1 Fire

Numerous authors (eg Wheaton et al., 1987; UK Department of Environment, UK, 1988; Fosberg, 1988; Street, 1989) state that changes in the frequency and seasonal distribution of forest fires are likely as a result of GHG-induced climate change. Wildfire frequency and severity is expected to increase throughout most of the unmanaged lands because of the projected increases in available fuel as primary productivity increases and because of the increased amount of dead fuel accumulating as a result of increased mortality.

In those forested areas where there is a decrease in soil moisture, drying of forest fuels will be enhanced, thereby increasing the amount of available fuel. Fried and Torn (1988) compared the changes in area burned under the current and a $2 \times CO_2$ climate in the California Sierra Nevada. They found that under the changed climate there would be a twofold increase in modest-sized fires (a few hundred hectares) and a threefold increase in fires greater than 1000 hectares. Street (1989) examined the effects of GHG-induced climate change on fire severity in Ontario, Canada. The projected changes in temperature and precipitation may not only increase fire severity throughout the fire season, but could also result in an increase in the length of the fire season and a shift in the timing of the most severe portion of the season from spring to late summer. This shift in fire severity could produce a more bimodal fire season with more severe periods during the early and late portions of the fire season.

Mortality in forests could increase under climate change because, with rapid changes in climate, many existing species will find themselves no longer centred in their climatic ranges. Fosberg (1988) suggests that under the proposed climate change and associated vegetation changes, fire activity will increase. He proposes that as a result of transient ecosystem changes (during which there would be increased mortality), there would be a temporary increase in fire danger before it would reach a level above current values but less than the transient peak.

Communities composed of species with short generation times, such as grasslands, should experience a shorter period of altered fire frequency, as dead fuel is combusted and new species colonise the area. Forests, in contrast, with longer generation times and lower natural fire frequencies, may experience a more prolonged period of frequent fires, as the dieback transition period would be expected to last for a century or more.

In areas with a distinct wet and dry season (parts of the tropics, and all of the Mediterranean-climate regions), changes in the amount of precipitation in rainy months could alter fuel loads by influencing growth. The altered fuel loads along with changes in precipitation could affect fire intensities during the dry season. A shift towards a slightly wetter climate during the summer rainy season (Menchaca and Byrne, 1990) could increase fuel loadings in most of the subtropical and temperate woodlands of Mexico which would suggest increase fire intensities.

In Mediterranean-climate regions, and fire-prone temperate regions such as the (Eucalyptus) forest area of Australia, where resprouting from plant stems and roots is a major avenue of regeneration following fire, increased fire intensity, with associated increases in stand mortality, could hasten species compositional changes, since regeneration would be slowed. Such a phenomenon has already been well documented in Mediterranean-climate shrublands (eg Westman and O'Leary, 1986; O'Leary and Westman, 1988). Under the influence of climate change, simulation models have demonstrated that higher fire intensities and shorter fire frequencies can induce rapid compositional changes in Mediterranean-climate shrublands (Malanson and Westman, in press). Fire could have a role in hastening compositional changes in less fire-prone ecosystems as well. In the tropical rainforests, which are normally too wet to burn, an increase in blowdowns from cyclonic storms, combined with enhanced mortality of individuals, could create a matrix of dry fuel that could carry a fire. The balance between rainforest and more fire-prone (Eucalyptus) forest in Australia, for example, has been shown to shift over time under the combined influence of climatic events and fire (Webb, 1958; Webb and Tracey, 1981). Increased human deforestation activities in the tropics would be expected to exacerbate such an effect. It has been suggested, for example, that the massive fire in the Kalimantan region of Borneo in the early 1980s was due to a combination of El Niño-driven drier weather, and increased deforestation activities in the region.

In tropical forests on poorer soils, fires can result in significant soil nutrient impoverishment, since much of the nutrient capital is held in above-ground parts. While many nutrients remain in the ash, key nutrients such as nitrogen and potassium are in part volatilised. In the long term, this could result in impoverishment of biomass. There is evidence that such a cycle of fire and nutrient loss on coastal sandy soils in subtropical Queensland, Australia, has led over a several thousand year period to reductions in biomass from forest to scrub stature (Westman, 1978).

4.5.2 Soil and surface stability

An increase in mass wasting of soil (slumping, landslides) is expected under the proposed GHG-induced climate changes because of the increased mortality of woody vegetation during the period of rapid climatic change and the relative slow growth of new woody species. Erosional losses and, on steep slopes, mass wasting and landslides, are expected to increase, especially in fire-prone areas where vegetative losses could be even greater. In areas where herbs and grasses move into an ecosystem, soil binding on some terrain would increase if there is rapid development of cover and root systems, although soil binding by herbs and grasses is generally less than that by shrubs and trees (eg Rice et al., 1969; Rice and Foggin, 1971).

Further contributing to changes in mass wasting of soils are the potential changes in precipitation and surface runoff. Although the influence of climate change on precipitation and surface runoff is uncertain, any change in their timing, intensity or duration will affect soil and surface stability.

Increased rainfall amounts alone will not lead to significant increases of soil loss if rainfall intensities remain unchanged (Kwaad, 1989). Increased rainfall intensities and/or an increased number of high intensity rainfalls will lead to an increase in the rate of soil erosion. Taking into consideration possible ecosystem changes induced as a result of climatic change along with increased rainfall amounts, however, could lead to increases in the rate of soil erosion. Kirby (1989) found a substantial increase in sediment yield forecasts, ranging from 40-400% for various locations in Mediterranean Spain as a result of a net increase in overland flows.

Transported material can also have an impact on systems through which it travels, as well as that at the source and target areas. In the case of water erosion, increased sediment loads in rivers and lakes can reduce water quality and impact on basin bathometry which can lead to increased vulnerability to flooding. Soil material can reduce visibility and incoming solar radiation (Owonubi, 1989) and, when it settles, may impact on yields of trees and other vegetation.

In the boreal and tundra regions, melting of ground ice leads to slumping of the overlying soil, thereby significantly affecting plant cover and associated wildlife as the pattern of water and terrestrial microsites. This process seems to occur first and most vigorously in the wetter parts of the landscape. That is of great importance to wildlife, because the sedge-meadow 'oases' of these regions are the most important feeding areas, both for herbivores (hares, geese) and for primarily insectivorous birds. If permafrost melting becomes widespread, there may be massive changes in the extent of prime wildlife habitat. In affected areas it may not take long for a vegetative cover to be re-established; and this replacement cover may differ significantly from that now existing (see Working Group II Report, Subgroup VII, for more details).

In the case of highly mobile mammals, disruption of the ecosystems through land use changes, land slumping and flooding associated with permafrost, ice break-up or sea-level rise will restrict their movements and, thereby have a deleterious effect on the health and survival of the animals. For example, open water between Arctic islands would prevent movement, stranding such species as lemmings (*Lenus* and *Discrostonyx*) and wolves (*Canis lupus*).

In addition to the climate-induced phenomena such as fire, salinisation, flooding and vegetation mortality that can lead to increased soil erosional losses, substrate can play a role in filtering vegetation composition changes through influences on nutrient and water availability. Of the 21 dominant species of coastal sage scrub in the Mediterranean-climate regions of Pacific North America, for example, 18 show strong substrate preferences (Westman, 1981). In tropical Australia, evidence exists for strong species preferences based on substrate fertility (Webb and Tracey, 1981). Pastor and Post (1988) use forest simulation modelling to show the role that soils of two different water-holding capacities could play in influencing the composition and productivity of forests in the current boreal/cool temperate forest margin over a 200-year period of climatic change. The influence of the soil is exerted initially on soil water availability, and hence species preference; however, a further feedback occurs as the lignin/nitrogen ratio of litter changes with species composition, since this in turn influences litter decomposition rates, and further availability of nitrogen for vegetation growth.

4.6 Sea-level rise

Based on a scenario for sea-level rise of 0.3-0.5 m rise by the year 2050, analyses suggest that there exists a potential for considerable local and regional variation in the magnitude of impacts. Variations in coastal topography, isostatic rebound, sedimentation patterns, coastal subsidence and human impacts may greatly influence the extent of effects.

Coastal natural terrestrial ecosystems (ie those areas under the influence of tidal or saline-water intrusion) will be profoundly influenced by sea-level change possibly leading to ecosystem disruption through inundation, erosion and saltwater intrusion (Titus, 1988). The wetland response will, however, depend on a number of factors: the magnitude of the rise in sea-level, tidal range, coastal topography, extent of anthropogenic development both along the coast and inland, sediment supply and the continuing presence of protection from high-energy waves and storm surges. Although coastal wetlands may form in more dynamic situations where the sediment supply is sufficient, on a global perspective they are most often found along low-energy coasts protected from waves and storm surges, particularly those coasts which are emergent or stable.

The dynamics and structure within an individual coastal wetland depend on the tidal regime and the flushing patterns. Typically a zonation of different vegetation types occurs as one moves from greater to lesser tidal influence and from saline to freshwater situations. Sea-level rise will tend to promote a landward displacement of these zones (although increased precipitation and runoff responses could enhance freshwater influences). A major issue, however, is the capability of coastal natural terrestrial ecosystems to move inland. The wetland habitats, for example, may accrete sediment at a rate keeping pace with gradual changes in sea-level, but the expected rise being discussed here may be too much. Destruction by increased salinity, subsidence and erosion may result. As an example, Rampino and Sanders (1981) believe that the <4000-year age of coastal marshes in the eastern US reflect a rise in sea-level 4000-7000 bp during which existing marshes could not sustain themselves.

Additionally, Stevenson et al. (1986) have shown that a significant rise in sea-level (due to subsidence) in the Blackwater Wildlife Refuge in Maryland (US) has led to a loss of one-third of the total marsh area (over 2000 ha) between 1938 and 1979. In Chesapeake Bay region on the US east coast, the declining numbers of wintering waterfowl have been attributed to erosion of wetlands due to subsidence (Stotts, 1985). In Louisiana, a complex set of effects including land subsidence, a loss of sediment input and channelisation through wetland areas has led to substantial losses of wetland (Meo, 1988; Baumann et al., 1984). It has been estimated that a rise in sea-level of about 1 m could lead to a near total loss of marsh and a reduction of 30% to 50% in the area of mudflats in Essex, UK (UK Department of Environment, 1988; see also Harmsworth and Long, 1986).

Boorman et al. (1988) provide a series of predictions for Britain's coastal areas with climate change and associated sea-level rise. In salt marshes, vegetation will be directly affected by more frequent and longer submersion. There will also be indirect effects from a more severe wave climate in deep areas. Most salt marsh birds nest on the ground and thus will be vulnerable to flooding. Many species feed on intertidal mudflats, where water levels affect the availability of food.

Modelling studies and field surveys of sites in the United States have illustrated that major losses of wetlands would be expected given a rise in sea-level. For example, under the scenario of a 16.8 mm annual rise in sea-level (ie 1.59 m in 95 years) by 2075, 84% of low marsh, 71% of high marsh and 45% of tidal flats would be lost in the Charleston, South Carolina, area without protection (Kana et al., 1986,1988a). The results are highly dependent upon the specific scenario of sea-level rise and location (Kana et al., 1988b).

It is clear from this example and other modelling exercises which have been undertaken (eg Armentano et al., 1988; Park et al., 1986, 1989) that considerable variation would occur from site to site and given different scenarios of sea-level rise. The consistent element among all published studies is that, overall, wetland loss will occur and that major changes may be expected in the distribution and type of wetlands.

Based on the assumption that wetlands could migrate inland and new wetlands would form in areas not flooded previously, Park et al. (1986) hypothesise that a 'high' sea-level rise (ie 1.6 m) could result in the loss of 45% of the 485,000 ha of coastal wetlands in the United States by 2100. A sea-level rise of 0.9 m could result in a loss of 22% of the wetlands.

However, even assuming a sufficient sediment supply to enable wetlands to accrete quickly enough to keep pace with a change in sea-level, wetlands' inland migration may be thwarted. In many areas throughout the world wetlands have evolved in concert with gradually changing sea-levels by accreting sediment into basins that otherwise would be open water. They now lie at the base of rising slopes which may limit inland migration. In addition, human settlement (eg seawalls and other shoreline protection structures, fish ponds, rice paddies and urban areas) immediately landward of coastal wetlands is common. This too would restrict the capability of wetland areas to migrate inland.

Other changes may have significant impacts on coastal wetlands. The sediment supply may be increased because of shore erosion, thus providing an additional source of material to wetlands. Increases of suspended sediment could, of course, reduce wetland productivity. As marshes erode with higher sea-levels, the sediments will be transported into the estuary, deteriorating habitats for traditional estuarine species (Kearney and Stevenson, 1988). The increased metabolism of cold-blooded animals due to warmer temperatures would increase their demand for oxygen. Since the area already has low O_2 in summer, the threat to sensitive species could worsen.

More significant, however, are likely changes in the erosive power of tidal currents due to changes in bathymetry and increased wave energies close to shore. Protective structures such as spits, barrier islands, baymouth bars and man-made structures are likely to be breached with rising sea-levels, thus allowing extensive erosion of coastal areas. The impact may be intensified if any increase occurs in the frequency or strength of storms. Indeed, changes in storm severity may have a most significant effect on coastal natural terrestrial ecosystems (Ramcharan, 1989).

Many tropical coasts are fringed by mangrove swamps which act as a buffer between the sea and inland areas. The swamps trap sediment and absorb wave and storm energy, thus fostering accretion which promotes the development of salt marshes. Mangroves are being planted in some areas for storm protection (Saenger et al., 1983). However, in many regions mangroves are disappearing on a large scale because of land reclamation, fish pond construction, mining and waste disposal (eg Soegiarto, 1985). Under natural conditions one would expect a landward migration of mangroves in response to a rise in sea-level. However, fish ponds and rice paddies are now often found landward of the mangroves; these may not be voluntarily abandoned to make room for the mangrove swamps (Rosenberg et al, 1989).

Increased sea-levels could imperil certain species with limited distributions in coastal areas. North Sea tidal floods in 1953 caused the extinction of the sole English colony of the damselfly ***(Coenagrion scitulum)*** from a low-lying site in Essex (Corbet et al, 1960). Given the potential for substantial losses of coastal natural terrestrial ecosystems, the numbers of any species limited in distribution to such areas could be adversely affected by a rise in sea-level. Many species of birds depend upon coastal wetlands, especially in the case of waterfowl and wading birds, many of which use coastal wetlands for feeding, wintering and staging areas. The loss of any substantial amount of coastal wetland could affect their populations and adversely affect use of the resource.

5 Socioeconomic consequences

Assessing the socioeconomic consequences of climatic changes for natural terrestrial ecosystems must consider not only the implications for man-made goods and services but all functional relationships between these ecosystems and human needs and activities (de Groot, 1988). This includes the capacity of natural and semi-natural ecosystems to provide goods and services that contribute to human welfare, directly or indirectly, through:

- their capacity to regulate and maintain essential ecological processes and life-support systems (eg climate regulation, watershed protection, storage and recycling of human waste, maintenance of biological diversity, biological control and provision of habitat);

- their capacity to provide resources (water, food and fabrics; building, construction and manufacturing material; fuel, medicinal, biochemicals, ornamental etc);

- their capacity to provide space and suitable substrate/medium for human activities (habitation, agriculture and husbandry, recreation, nature conservation etc); and

- their capacity to provide opportunity for cognitive development (eg aesthetic, spiritual/religious, educational and scientific information, and cultural and artistic inspiration).

The total socioeconomic value of a given ecosystem represents only the annual return from the respective functions. Since ecosystems can provide environmental goods and services in perpetuity through sustainable utilisation, the total annual value should be transformed into a capital value to reflect the true economic value of the ecosystem as a producer of goods and services (de Groot, 1988).

Local or regional loss of these environmental functions through ecosystem disruption could cause environmental damage which may have considerable economic consequences. Many environmental functions, especially the 'free services', provide considerable economic benefits which do not show up in economic accounting procedures until they are damaged or no longer available. Mitigation costs to respond to losses of these functions could be excessive or impossible to mitigate and include increased dependence on water and air purification faculties, enhanced rehabilitation programs (eg reforestation) and artificial erosion prevention projects.

When attaching market prices to certain goods and services, it must be realised that there exist many different market-places with different value standards. So-called minor forest products may have a very low value (or no value at all) on the international (export) market, although they are valuable to the national economy or to local communities, notably indigenous people.

5.1 Unmanaged vegetation and forests

Unmanaged vegetation and forest areas have great value since significant portions of the world's economy (eg forestry and tourism) are built on their sustainability, despite the fact that many of these areas are not used sustainably. Tropical forests of the Asian region produce approximately 500 million m^3 of fuelwood and 100 million m^3 of industrial wood annually generating more than $5 billion in foreign exchange earnings. Numerous communities throughout the forested regions of the world rely solely on the forest and the income derived from forest products for their existence (eg approximately 350 communities in Canada alone). In addition, other sectors of the population rely on these areas for their recreation, aesthetic and wildlife value.

The value of 'minor' forest products provides a major source of income for many developing countries; disruption of the ecosystems which provide the required resources could result in local and possibly regional socioeconomic problems. In Indonesia during 1975, exports of minor forest products including fruits, nuts, birds' nests and feathers, had a market value of $26 million (Jacobs, 1982). The worldwide sale of rubber is estimated at $2.6 billion annually (Oldfield, 1984) and for rattan approximately $1.2 billion annually (Jacobs, 1982).

In Canada, the area of continuous boreal forest is estimated to be 148 million ha of which 80 million ha are currently economically accessible. It is of concern that this estimate is smaller that the 100 million ha which are projected to become climatically unsuitable for boreal forests under the proposed climate change {Sargent, 1988).

Consideration will have to be given to the potential impacts of climate change on forested ecosystems when considering the appropriate harvesting techniques for a particular stand (ie clearcutting vs selective cutting). In those areas targeted for harvesting and where forest (and ecosystem) health is suffering, clearcutting followed by appropriate reforestation (eg an alternative species or mix) may be a viable option for some species (not for hardwoods). In those situations where the current forest stand continues to be healthy (ecologically, socially and economically), consideration should be given to restricting harvesting to selective cutting. This would help maintain the existing forest climate, reduce the disruption caused by stresses imposed by climatic change, and maintain the ecosystem, especially for some hardwood species. In addition, the likelihood of fires and fire intensity should be considered in managing debris and removal of deadwood.

The carrying capacity of rangeland in arid and desert areas of Africa (Le Houerou and Popov, 1981; Kassam and Higgins, 1980) has already been exceeded and is being approached in semi-arid regions. Consequently, the amount and distribution of rainfall and other changes in productivity under proposed climate change becomes a critical variable in determining the viability of pastoral societies in arid areas of Africa (Le Houerou, 1985).

Some tree species in China will be adversely affected by projected changes in climate, thus causing some difficulties for its timber industry, especially at the regional level (Rugiu, 1990). ***Larix gmelini*** and ***Larixolgensis*** do not appear to be susceptible. ***Pinus Korajensis,*** which currently can be found in the southwestern portion of northeast China, however, will be negatively affected both as a result of increased climatic stress and owing to increased disruption from fire. ***Lanceotata,*** which represents approximately one-fifth of the national output of commercial timber, will suffer as a result of higher summer temperatures. Productivity will decrease and death is projected. ***Pinus Masoliona,*** which accounts for approximately one-half of the forest reserve of southern China would retreat southward and productivity of those forests remaining would decline. ***Pinus Yunnanensio,*** the major timber species of southwestern China could decline considerably with its habitat changing over to nonproductive, hot or warm shrubs and grasses.

An acceleration in the rate of perturbation will increase the vulnerability of marginal lands already experiencing pressures from various sources. In the case of Aboriginal lands of Australia, changes to these ecosystems as a result of proposed climatic changes threaten the conservation value of the lands and a subsistence component of the Aboriginal economy, which is valued in the order of tens of millions of dollars per annum. Many Aboriginal people receive over 50% of their income from natural resources and any reduction in the availability, amount or quality of these will push these people below the poverty line.

Changes in wildfire intensity and frequency within unmanaged vegetation and forest areas will have significant socioeconomic consequences. Within Mediterranean communities, forest and shrubland wildfires would grow exponentially (4.7% annually) (Le Houerou, 1989) putting a heavy burden on these communities. Around the Mediterranean Basin, 650,000 ha burnt on an annual average between 1980-86 at a total cost of $1.2 billion. In Italy during 1988, a particularly dry and hot summer, about 13,500 fires burned an area of 186,000 ha (60,000 ha forested lands) with losses in forest production estimated at $46 million, six people killed and 80 injured.

Significant losses within boreal and temperate forests are commonly the result of infestations by pests such as the spruce budworm, pine mountain beetle and tent caterpillar. In 1980, over 5 million lodgepole pine trees covering 156 000 ha were killed by mountain pine beetle ***(Dendroctonus ponderosae)*** in the province of British Columbia, Canada. This is a twofold increase in the area over that recorded in the previous year.

Increased soil erosion will result in increased costs of clean-up of sediments from urban infrastructure. The cost of clean-up of erosion sediments as a result of the decline or death of 2000 ha of conifers from ozone pollution in the San Bernardino Mountains of

California was estimated at $27 million annually (Westman, 1977).

About 80% of the forest production in developing countries (47% worldwide) is currently used as fuel. The principal, and sometimes only, source of fuel for perhaps one-quarter of the world's population is fuelwood and fuelwood consumption in the tropics alone is estimated at more than 1 billion m^3/year. By the turn of the century, 3 billion people may live in areas where wood is cut faster than it grows or where fuelwood is scarce. Suggested changes in the forests of these areas could reduce the availability of fuelwood, especially in those areas where climate change will cause a shift in species. During the transition period, damage caused to the ecosystem by over-grazing and over-harvesting will result in disruption of the substrate, exacerbating the fuel-wood situation as new species will find it difficult to become established in these nutrient- and moisture-impoverished areas.

Fuelwood-gathering opportunities could increase in forests subject to increased mortality, but since the concomitant risk of fire increases, it seems likely that a substantial fraction of potential fuelwood could be combusted in wildfires and hence be lost to domestic uses. In the southern portions of the Mediterranean Basin most of the forest and shrub-land would be cleared for cropping, or destroyed by heavy overgrazing and fuel collection (Le Houerou, 1989).

Northern latitudes are likely to experience an increase in tourism as the duration of their summer climates will be extended, and visitors from lower latitudes seek cooler locations for recreation. Similar ramifications are likely for higher elevations in alpine environments.

Opportunities for grazing activities in lower latitudes could expand, based on the expected expansion of grassland areas (Emanuel et al, 1985). Where fire frequency increases, the opportunity to convert recently burned forest or shrubland to rangeland will increase, further accentuating the tendency for rangeland to expand.

Supporting many local communities are incomes associated with the cc" lection and trade for orna- . . . . .!.?'. ⇒nd decorative purposes of biotic resources (eg certain minerals) a id many plants and animals (eg orchids, butterflies, aquarium fish). In addition, forested and natural vegetation areas provide many types of materials for handicraft (eg wood and other carving materials, hemps, leaves and other materials used for weaving and basket making) and objects for worship, such as products associated with cultural, tribal and religious ceremonies.

5.2 Biological diversity and endangered species

There are multiple social and economic consequences of changes in biological diversity and status of endangered species. Currently, experts estimate that the number of species on earth is between 5 and 30 million (Wilson, 1988) with only 1.5-1.7 million species known to science. In the course of history, people have utilised about 7000 kinds of plants for food (Myers, 1984); predominantly wheat, barley, rye, oats, rice, maize and about a dozen other highly domesticated species. Yet there are at least 75,000 edible plants in existence, and many of these could be superior to the crop plants in widest use.

The following examples give an indication of the social and economic consequences of the impacts of the proposed GHG-induced climate change on biological diversity and endangered species.

Native plant species supply about 50% of the raw materials for pharmaceutical manufacturers and continue to play an important role as reservoir of potential new drug sources. The World Health Organization estimates that 80% of the people in developing countries rely on traditional medicine for their primary health care needs, and 85% of traditional medicine involves the use of plant extracts. This means that approximately 3.5-4.0 billion people rely on plants as a source of drugs (Farnsworth et al, 1985).

Estimations of annual sales of drugs and other pharmaceutical products derived from, or containing products of plants and animals range between $8 and $20 billion per year (de Groot, 1988). Several currently used drugs for the HIV virus associated with AIDS, for example, are from natural sources: castanospermine from a Queensland rainforest tree; tricosanthin from the root of a Chinese cucumber plant; vincristine and vinblastine from the African periwinkle. In 1985, total domestic and international sales of these two drugs alone were approximately $100 million (Wilson, 1988). Species extinctions expected as a result of climate change could threaten important sources of new drugs.

Endemism is a feature of a wide variety of wetland animals (Maltby, 1986). As a result many of these species are rare, threatened or endangered. Since the morphology of many endangered or rare plant species in wetlands is indicative of poor competitive ability (Moore and Keddy, 1989), even climate change to more amenable conditions may put some existing wetland species at a comparative disadvantage.

Changes in habitat and the availability of food and water will increase pressures on animals and may lead to many animals having to migrate and/or disperse over larger areas. In the case of endangered species, dispersal could be disastrous. For those species for which numbers are already low, reproductive potential will decline as the number of times that males and females meet during periods when fertilisation is possible decreases. In the case of herding animals, dispersal could lead to traditionally non-dominating males fertilising the females, thereby reducing the genetic health of the population (Cubberly, 1989). Clearly, anything which adversely affects the already threatened species such as the African elephant (population 400-600 thousand) and the black rhino (population less than 3000) are of great economic concern. McNeely (1989) estimates that an elephant herd in a Kenyan national park provides over $600,000 per year to the nation's economy through the associated tourist industry.

The projected reduction in Norway (from 30% to 7%) of the area classified as alpine (Holten, 1990b) could result in substantial changes in, and possible losses of, habitat for alpine plant and animal species. It is estimated that plant species currently above 1300-1400 m would be threatened by climate change owing to invading forest combined with low dispersal capacity for many mountain plant species, eg ***Campanula uniflora,*** *Knutsh0* ***Poa (Poa stricta)*** and 10-15 other middle-to-high alpine species. The total reduction of grazing areas and the possible change of species composition of the lichen-dominated vegetation in the continental areas of Scandinavia could have adverse effects on the reindeer and indirectly on the wolverine.

Habitat loss will also affect many bird species through loss of nesting locations (eg Arnold, 1988). Species that could be affected include the red-tailed black cockatoo ***(Calyptorhynchus magnificus),*** the regent parrot ***(Polytelis anthapeplus)*** and boobook owl ***(Ninax novaeseelandiae)*** all of which nest in tree hollows in Australia.

Agriculture has reaped the benefits of the genetic resources of natural species. A wild wheat plant from Turkey provided genetic material that improved disease resistance to commercial wheat varieties worth $50 million annually to the US alone. A wild variety of corn (maize) from Mexico when crossed with modern corn varieties will, based on estimates, provide a potential saving of $4.4 billion annually worldwide. Major cultivars of crops, improved by genes from natural species have a combined farm sales value of $6 billion annually in the US. The projected impacts on species diversity will affect the genetic base required for the continued improvement and maintenance of currently utilised species and deprive the world of the potential to develop new ones.

5.3 Wetlands

Changes in wetland numbers, type and distribution can affect the social and economic values based on these areas. Several studies have provided economic analyses of wetland values (eg Morzer-Bruijns and Westhoff, 1968; Gosselink et al., 1974; Raphael and Jaworski, 1981; Thibodeau, 1981; Farber and Costanza, 1986). Despite methodological problems, without exception these have demonstrated not only the significant magnitude of, but also the variety of, benefits derived from wetland areas. The values are often remarkably high; for example, the capitalised values for mangrove wetlands have been given as $US212,507/ha (Thorhaug and Miller, 1986) and $US81,975/ha (Logo and Brinson, 1979). Values calculated for other wetlands have even been higher (eg Gosselink et al., 1974; Logo and Brinson, 1979). In any case, the potential for economic loss may be substantial.

Perhaps the most significant aspect of potential impacts of climate change in wetlands is that these will take place in the context of consistent losses of these areas globally. It has been estimated that 50% of the world's wetlands have already been lost (Maltby, 1986). The primary causes have been as a result of drainage and agricultural developments, projects for flood control, inundation in dam reservoirs, disease eradication ventures, channelisation, peat mining, deforestation etc. In many instances these undertakings are subsidised.

Among wetland organisms potentially affected by climate change are those of economic importance including: food fish, shrimp, oysters, waterfowl and fur-bearing animals, as well as plant species of value for lumber, food and fibre. Some of these are probably sensitive to changes in climate. For example, decreases in wet season rainfall in northern Australia have been interpreted as the cause of a substantial reduction in optimal nursery habitat for the important food fish, barramundi, and a reduced survival for young-of-the-year fish (Griffin 1985).

The loss of coastal wetlands imperils many values. Of particular concern is the dependency of many marine fisheries on the nursery habitat provided by wetland areas. A direct relationship has been shown to exist between the extent of tidal wetlands and estuaries and the productivity of shrimp fisheries (Turner, 1977). Many coastal wetlands which are highly productive in support of fisheries may be affected by higher sea-levels. On the positive side, New Zealand (1989) and Stokoe (1988) predict that a warming trend could benefit the aquaculture industry which could expand to higher latitudes. In addition, warmer sea temperatures should allow faster growth of fish, less risk of fish mortality during over-wintering as well as reduce energy costs in shore-based facilities. Unfortunately, warmer waters may also be more conducive to outbreaks of algae and bacteria that render molluscs unfit for human consumption.

Some examples may serve to illustrate the value of wetland dependent fisheries. Mangrove forests in Thailand are estimated to have an annual worth of $US130/ha in fisheries as compared to $US30 for charcoal production (Christensen, 1983). In 1976 the value of wetland-dependent commercial fish caught in the US was appraised in excess of $US700 million (Peters et al, 1978). Shrimp exports from developing countries earn $900 million annually (Maltby, 1986). The loss of substantial wetland areas potentially imperils these values.

The value of the loss of one mile of oceanfronting wetland has been estimated as $US69,857 as measured in increased damage potential from hurricanes (Farber and Costanza, 1986). Although wetlands do not tend to develop along high wave/current energy shores, the potential loss of coastal wetlands' protection is of concern.

The numbers of birds may be great for certain wetlands. For example, the intertidal areas of Mauritania's Banc d'Arguin harbour 30% of Atlantic flyway shorebirds and about 3 million migrants use the Senegal delta (Maltby, 1986).

5.4 Wildlife and fish

Wildlife and fish have both social and economic value. From a social perspective and beyond that already mentioned under biological diversity, wildlife and fish have recreational and aesthetic value as well as contributing to the preservation of aboriginal lifestyles. From an economic perspective, wildlife and fish provide sustenance and income (food, furs and tourism) for many communities in the world.

While there will be winners as well as losers among wildlife and fish subjected to climatic change, it is important to keep in mind the economic values which are at stake. Wild species provide the base for a worldwide, multibillion tourism and recreation industry - the most important source of foreign income in Kenya and Ecuador. Canadians spend more than $5 billion annually on wildlife-related activities, and in some areas of Botswana, animal protein provides more than 90 kg of protein per person annually (McNeely, 1989). These living natural resources are essential to the cultural and economic well-being of aboriginal peoples around the world, and they enrich the lives of all of us.

Wildlife harvest continues to be a livelihood for some, a sport for others. Since most natural ecosystems, excluding grasslands and deserts, could experience increased mortality and associated short- or long-term losses in productivity, wildlife and fish will be affected, with many species initially suffering a decline in numbers as habitat and food availability is disrupted. In many countries, there is still a great dependence on wild resources as a source of food, trade, medicine and construction materials. Sale (1983) indicates that in many African countries, there is an economic dependence on wild resources and that loss of access to wild animals and plants would result in a complete collapse of the traditional economy.

Russell et al. (1988) indicate a potential threat to the Porcupine River Caribou Herd, presently numbering some 165,000 animals in Alaska, the Yukon and the Northwest Territories. In summer, the herd moves northward beyond the treeline, in part to escape biting insects. A northward expansion of the boreal forest could leave the caribou without a refuge from the insects. Caribou agitated by biting insects may reduce their feeding and run until exhausted. Since this is one of the largest concentrations of free-ranging mammals on earth, providing sustenance for thousands of aboriginal North Americans, the effect on the health of the Porcupine herd could be significant.

Loss of breeding, staging and wintering habitat for waterfowl and shorebirds could be significant. Major areas of significant waterfowl and shorebird production, for example, lie in the continental climate areas of North America and Central Asia (Boyd, 1982; Isakov and Shevareva, 1968; Henderson, 1989). Historically, the loss of prime breeding habitat during drought periods has caused significant decreases in populations of waterbirds (eg CSIRO, 1987; Boyd, 1989).

Changes in these wetland areas can have significant impacts on waterfowl populations (eg Skinner, 1989; Whitman and Meridith, 1987). This will compound the existing threats from agriculture and other intrusions on a wildlife resource which provides recreational opportunities for millions of hunters and birdwatchers (the US and Canada have committed themselves to spending $1.5 billion to protect these threatened habitats under the North American Waterfowl Management Plan). Recreation, commerce and subsistence dependent upon these species would then be altered.

In northern latitudes, salmonoid species, such as lake trout and lake whitefish could be adversely affected and, in some areas, become extinct in shallow lakes as the cool bottom waters warm up (Hecky, 1987). Glacial residual elements in food chains could be eliminated from much of their present habitat.

5.5 Heritage sites and reserves

Socioeconomic consequences of the impacts of climate change on heritage sites and reserves are mainly related to increased pressures for alternative use of these areas and their resources and loss or disruption of these areas, with implications for changes in management strategies and recreation and tourism opportunities.

Areas currently set aside as parks, sanctuaries and reserves may eventually prove not to be adequate to protect specific ecosystems and species as climatic changes come into play, either because of their geographic location or size. As climate changes, resource abundance may decrease, causing economic stress and forcing local peoples to intrude on protected areas in order to acquire basic essential needs. The Sunderban forest in southwestern Bangladesh is a 580,000 ha tract of mangrove. In addition to being managed for timber, the area also produces fish, honey, wax and thatch. But it is as a wildlife reserve that it is best recognised around the world. There is considerable potential for tourism based on wildlife (Munshi, 1985).

Global warming may alter recreational opportunities. Heritage sites that encompass wetlands may be particularly affected. If fresh water levels drop, the character and recreation potential of shorelines will change. In some cases, there may be a reduction in recreation potential as waters recede and in others, wetlands may migrate with water levels (Wall, 1988).

In northern climates, participation in dry terrain summer activities such as hiking and camping will probably benefit from an extended season. However, risk of environmental deterioration will also increase as heritage sites experience more uses for longer periods (Wall et al, 1986).

Winter recreational activities will be influenced by a shorter season. Opportunities for skiing may be reduced or eliminated in some areas (Wall 1988), implying a possible expansion of this activity into more northern areas. The economic impact to existing ski operators could be substantial. Investment in high-capital costs for snow-making devices, high operating costs and a shortened ski season may greatly reduce the feasibility of some operations (Wall, 1988; More, 1988). A decrease in the length of the ski season will result in recreationists reducing expenditures in local economies (Wall, 1988; Lamothe and Periard 1988; More, 1988).

Public attitudes to the environment in heavily industrialised countries are changing, with a shift from a 'consumer' to a 'conserved society. Associated with this is a shift from consumptive recreational activities (eg fishing and hunting) to appreciative activities (eg hiking, biking, canoeing). A shift to pro-environmental attitudes would increase demand for heritage sites in which to recreate, and increase tourism in those areas that can supply pristine environments.

As sea-levels rise, prime agricultural land in low-lying coastal areas such as Bangladesh, Vietnam, China, Iraq and Egypt may be lost (Harrison, 1984). This may result in increased pressure to shift or expand agricultural production into existing or potential heritage sites to feed the world's growing population. In northern climates, the world's major grain belts of Canada, the US and Russia will experience longer, dryer growing seasons. These areas, while still capable of supporting agricultural production, will require more irrigation (Arthur, 1988; Harrison, 1984), putting increased pressure on already diminishing fresh water supplies. Pressure to divert water directly from heritage sites or interfere with flow to the sites will probably increase.

6 Future deliberations

While the specific impacts of global warming on any one region or a single species are still matters of conjecture, there are some clear conclusions that can be made. Natural terrestrial ecosystems will change in make up as composite species shift in location, and those species which can adapt will survive. The more sensitive ones, especially those for which options are limited, will dwindle or disappear. The best solutions to the ecological upheaval resulting from climatic change are not yet clear. In fact, little attention has been paid to the problem. What is clear, however, is that these climatological changes would have tremendous impact on communities and populations isolated by development and by the middle of the next century may dwarf any other consideration.

Examination of the environmental impacts of climate change on natural terrestrial ecosystems and the associated socioeconomic consequences is in its infancy. The number of studies that have been done are limited with only specific regions and sectors having been examined. Further limiting these studies is that, for the most part, existing studies have taken a narrow view of the problem and have not looked at it from a multidisciplinary perspective. In addition, most of these have examined climate change effects on current social, economic and environmental systems and not considered social and economic adjustments nor impacts and consequences during ecosystem transitional periods.

These limitations need to be addressed to provide more realistic answers regarding the possible impacts and, thereby, to allow the development of viable and effective response strategies. This can be achieved through various means including:

- Assembly of relevant inventories of species and ecosystems on a regional and international basis. A consistent baseline must be established in order to reach consensus on resources at risk.

- Integrated monitoring programs including biological, physical and meteorological parameters on a regional, national and global basis. 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 for establishing a network of benchmark sites. Monitoring of more sensitive ecosystems and species (as described in section 1.2 above) should be given priority since they would provide early indication of impact of climatic change. Also to be considered as a priority are those ecosystems and species which have significant social and/or economic value. This would suggest that concurrent social and economic data should also be collected and archived in an accessible manner.

- More information is needed on the relative sensitivities of species and ecosystems to climate and climate change. This is especially true for wildlife for which very little information is available. 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. Also of interest 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. More realistic would be examining the impacts and consequences with fixed societal and environmental changes or, better still, with a responsive society and environment.

- Impacts programs capable of these latter types of analyses would need to be multidisciplinary involving not only physical and biological scientists but also representatives from the social sciences and economics. National and international research funding programs should be capable of recognising and supporting this type of research. Research programs at the national and international level which examine the impacts of climate change and the socioeconomic consequences of these changes should be established where they do not exist and, should receive sufficient funding. The Climate Impacts Program of the UNEP should be strengthened. Efforts need to be directed towards identifying sensitive ecosystems or components thereof both from an environmental and socioeconomic perspective, determining the likely impacts and possible response strategies. One possible mechanism for carrying out these programs would be the establishment of regional programs or task forces which would promote and coordinate the development of regional impacts and consequences research, and the development of problem specific response strategies. This type of activity could build on already existing structures within WMO and UNEP.

- Comprehensive strategies and measures for the maintenance of biological diversity should be established on a global, regional and national basis. Natural terrestrial ecosystem managers and those involved in making decisions that affect these ecosystems must be aware of the potential risk that these systems are under due to climate change, the likely changes to these systems, the implications of their decisions, and options for responding and associated risks. This can be accomplished by various education and information programs. Foremost, however, is the involvement of these people in the assessment of the impacts, consequences and response options. Managers and decision makers need to be aware that policies and procedures should be flexible to accommodate the implications of climate change and the dynamics of this change as they are the ones who must decide on whether or not intervention is needed.

- Involving local peoples in the discussions on the future and in the development and maintenance of natural terrestrial ecosystems has far-reaching benefits. Initially societies respond at the local and regional levels of government through the actions of coalitions of local people. Support for establishment and maintenance of sites may be the highest at the grass roots level, involving local peoples. Fostering this involvement can provide social (eg the Elephant Action Campaign, Namibia) and economic benefits as it provides an alternate source of income (Lusigi, 1981; Penfield, 1989) and at the same time creates a better understanding of, and higher level of commitment to, developing and maintaining natural terrestrial ecosystems. Local and regional levels of government should be encouraged to become involved in protecting natural terrestrial ecosystems especially heritage sites and reserves.

- The more fragmented and the smaller populations of species are, the less resilient they will be to the new stresses brought about by climatic changes. Thus, one direction in the short term is to minimise further encroachment of development upon existing natural ecosystems. Meanwhile, efforts to improve techniques for managing communities and ecosystems under stress, and also for restoring them when necessary, must be carried forward energetically.

- In the near term, the critical needs of natural terrestrial ecosystems which face the most deleterious impacts should be addressed. Humans must be prepared to intervene where vital ecosystems or species are in jeopardy. Priority should be given to considering the various response options available and associated unknowns and risks. Consideration should also be given to reducing major human-caused stresses such as logging, subsistence domestic animal grazing and pollution-causing activities. Often, once these stresses, which may originate outside the boundaries of the ecosystem, are reduced, the elasticity of the affected ecosystem increases, possibly decreasing the impacts of climate change.

- In some cases, intensive (costly) management may be required to mitigate the effects of climatic changes. These could include transplanting key species and assemblages; the expansion or relocation of heritage sites and reserves; the establishment and maintenance of travel corridors (Peters, 1988) to allow dispersal of the inhabitants of restricted areas; and mitigating measures for wetlands (Titus, 1985; Louisiana Wetland Protection Panel, 1987) such as artificially nourishing marshes with sediment, preventing coastal developments from impeding the inland movement of wetlands, dyking, artificially controlling water levels and restoring barrier islands. Establishment of adequate reserves in selected areas which consider the implications of climatic changes so as to provide protected areas for ecosystem re-establishment. All of these possible solutions have major problems related to cost and long-term effectiveness. Intervention of this type, however, needs to be based on sound and comprehensive information in order that it be constructive rather than destructive.

Figure 3.1a Changes in climate zones currently associated with specific vegetation (Leemans, 1989) - Western Hemisphere

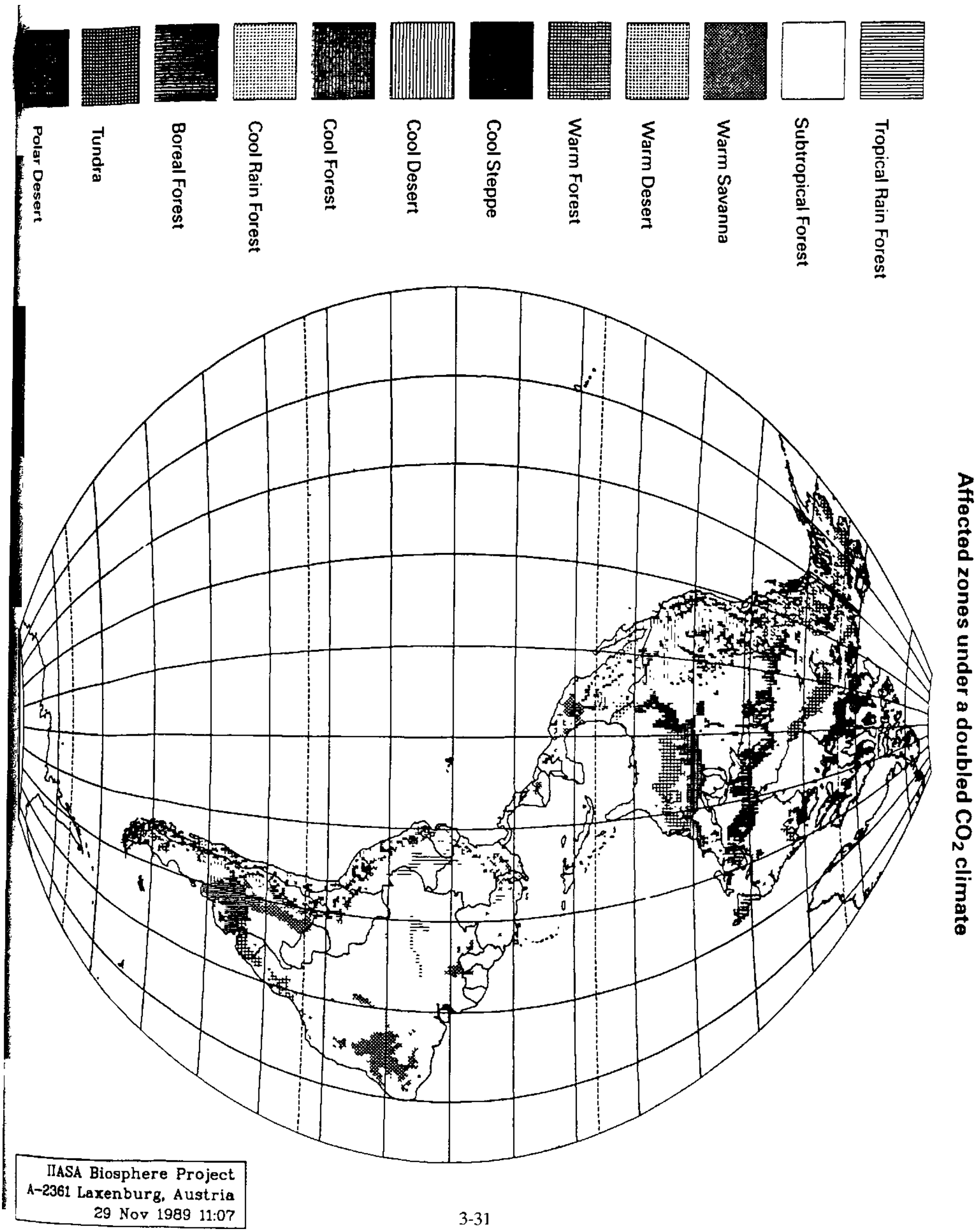


Figure 3.1b Changes in climate zones currently associated with specific vegetation (Leemans, 1989) - Eastern Hemisphere

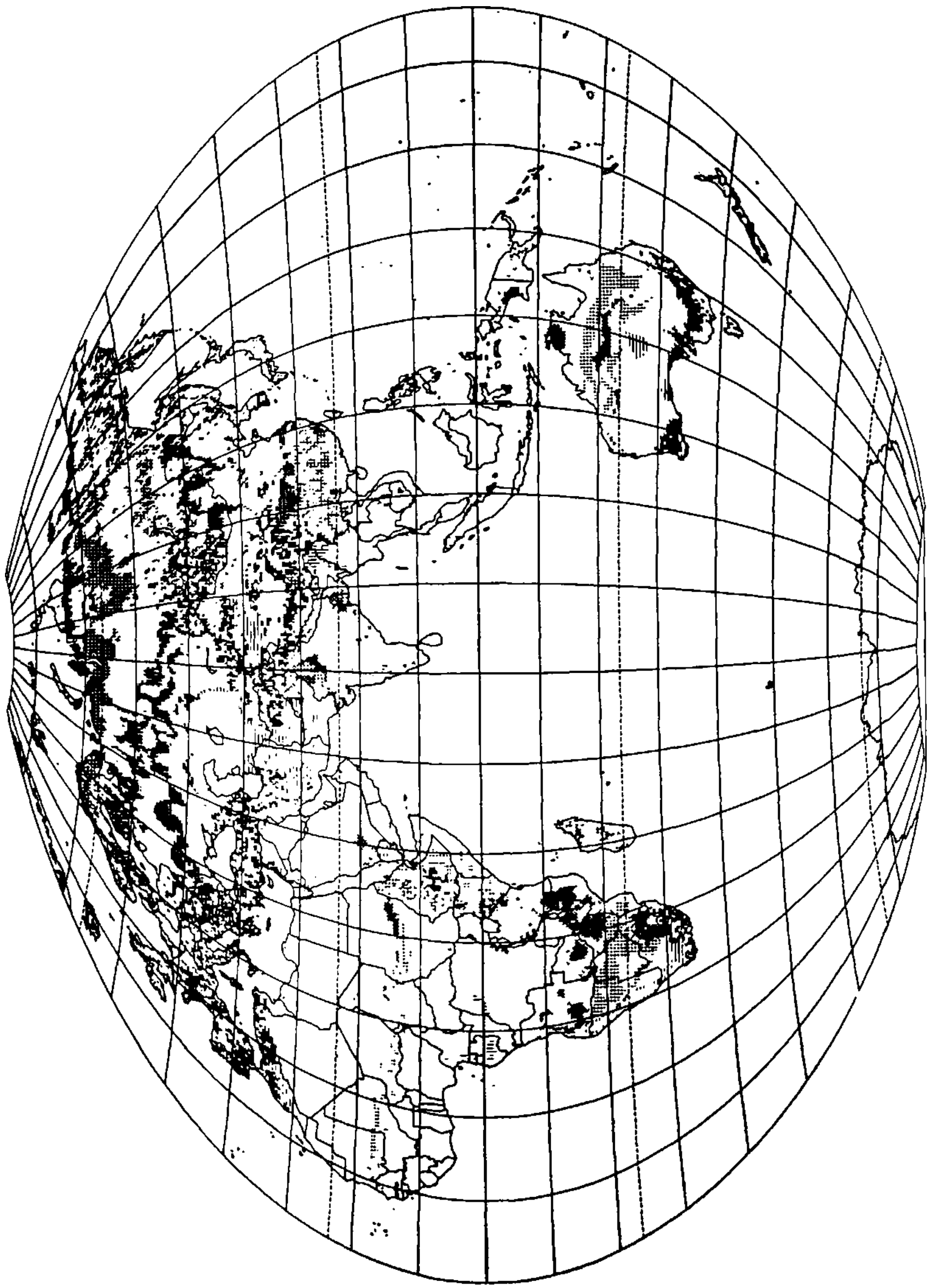


Figure 3.2a Potential changes in the distribution of the main tree species as a result of projected increases in temperature in the European part of the USSR along a transect at 50°E longitude (Velichko et al., 1990) - increase in global mean temperature of 0.8-1 °C

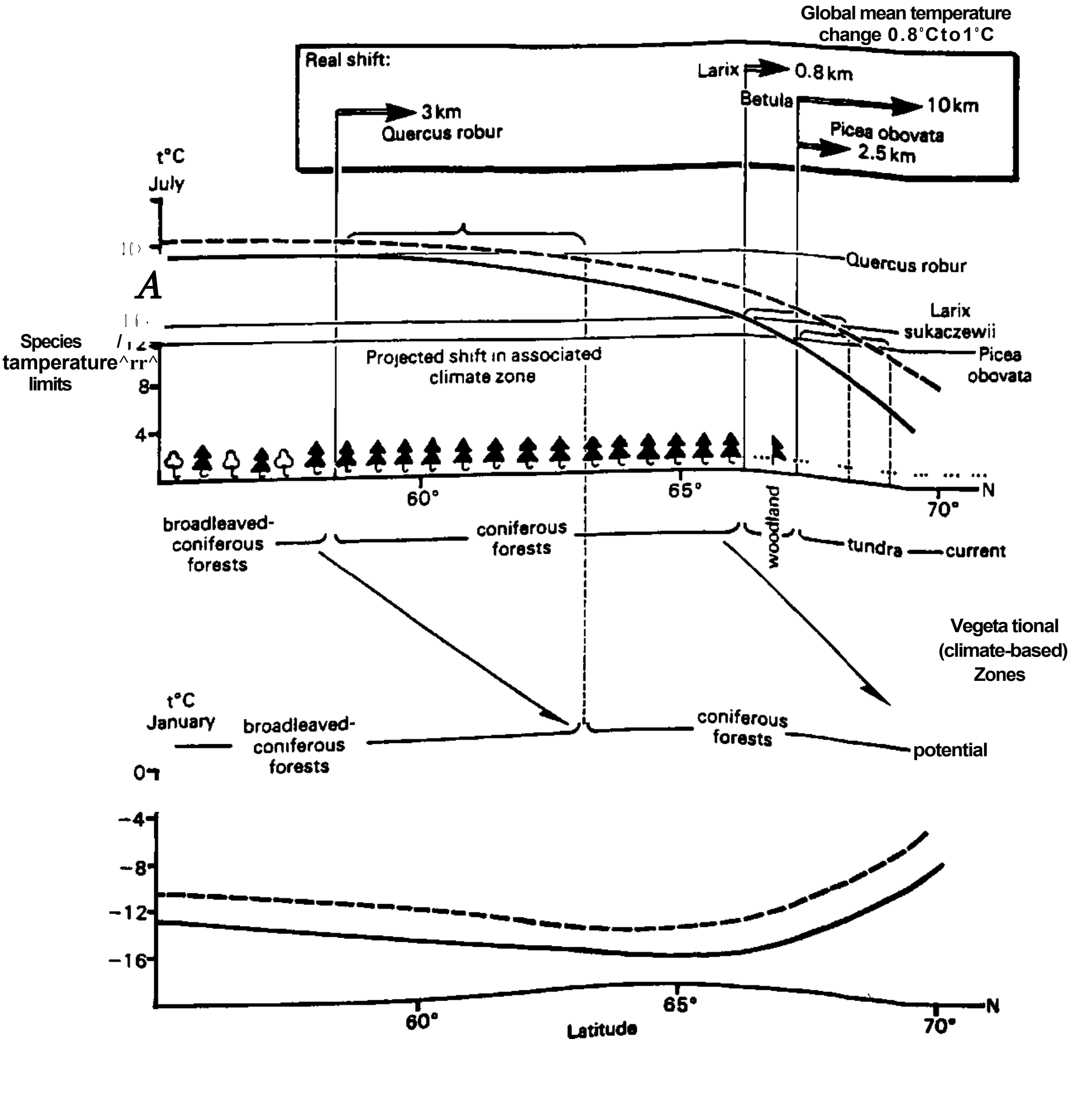
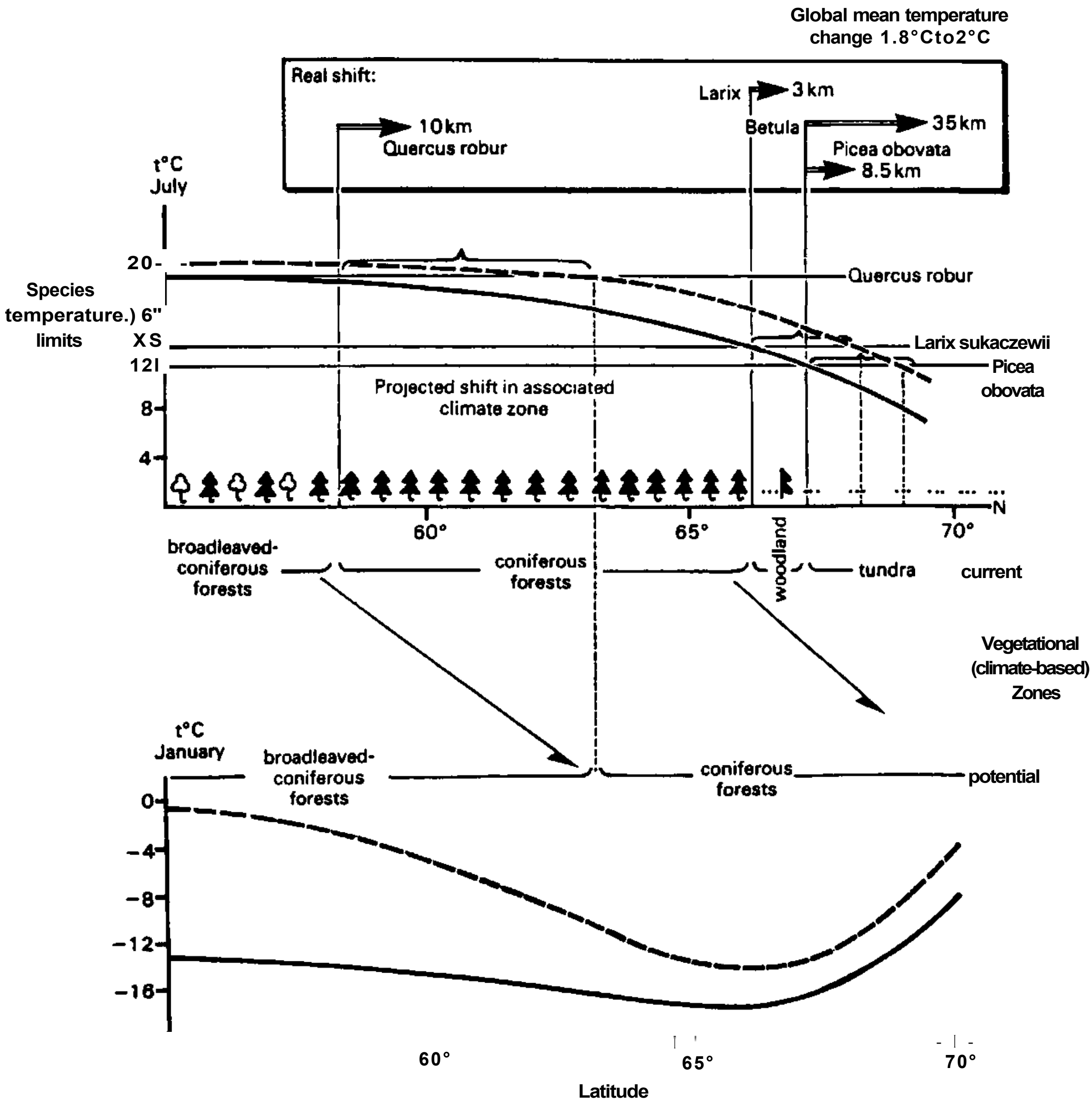


Figure 3.2b Potential changes in the distribution of the main tree species as a result of projected increases in temperature in the European part of the USSR along a transect at 50 °E longitude (Velichko et al., 1990) - increase in global mean temperature of 1.8-2°C



Finure 3 3a Potential changes in the distribution of the main tree species as a result of projected increases
g **temperature** in Canada along a transect at 100°W longitude (Velichko et al., 1990) - increase in global mean temperature of 0.8-1°C

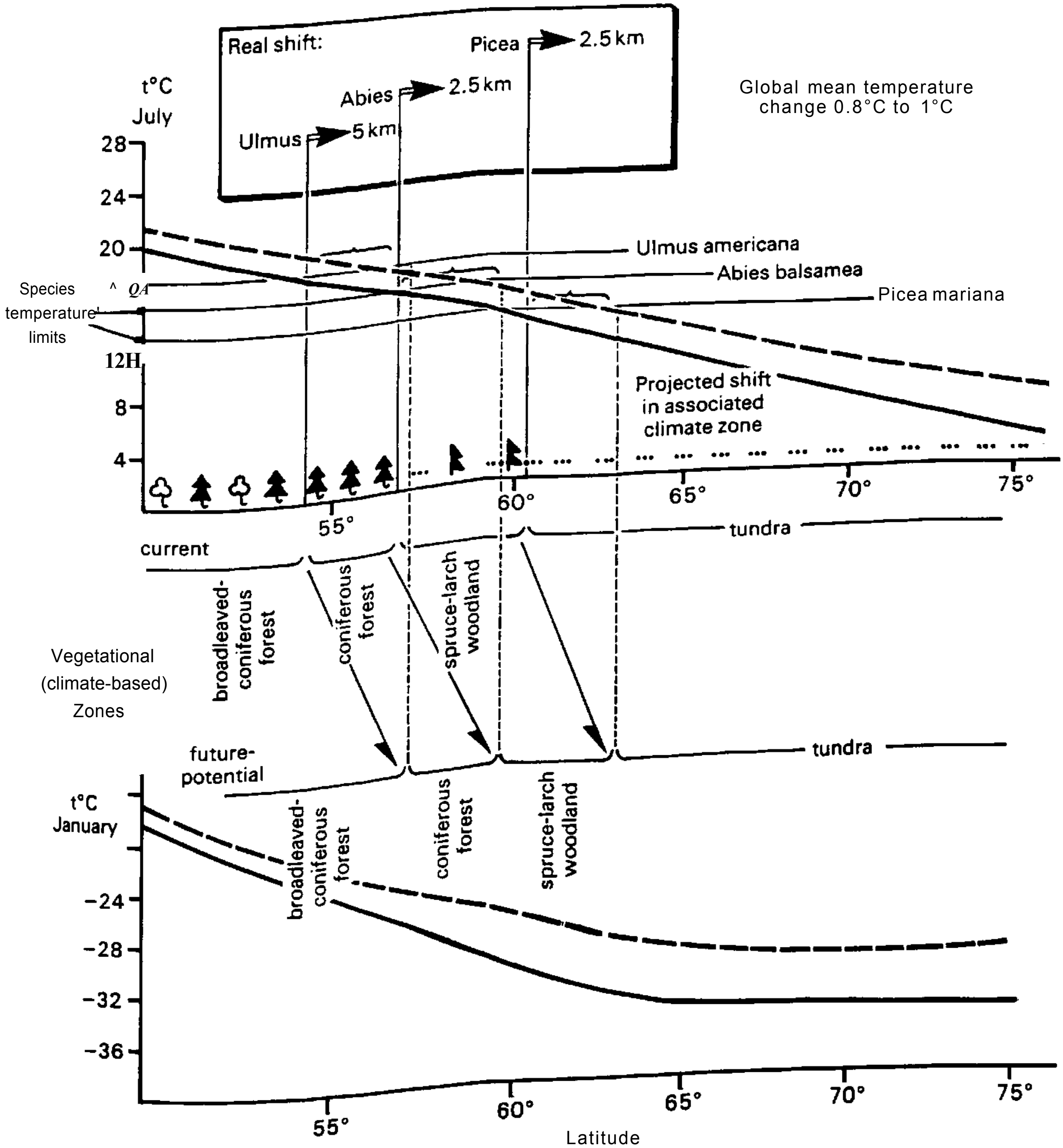
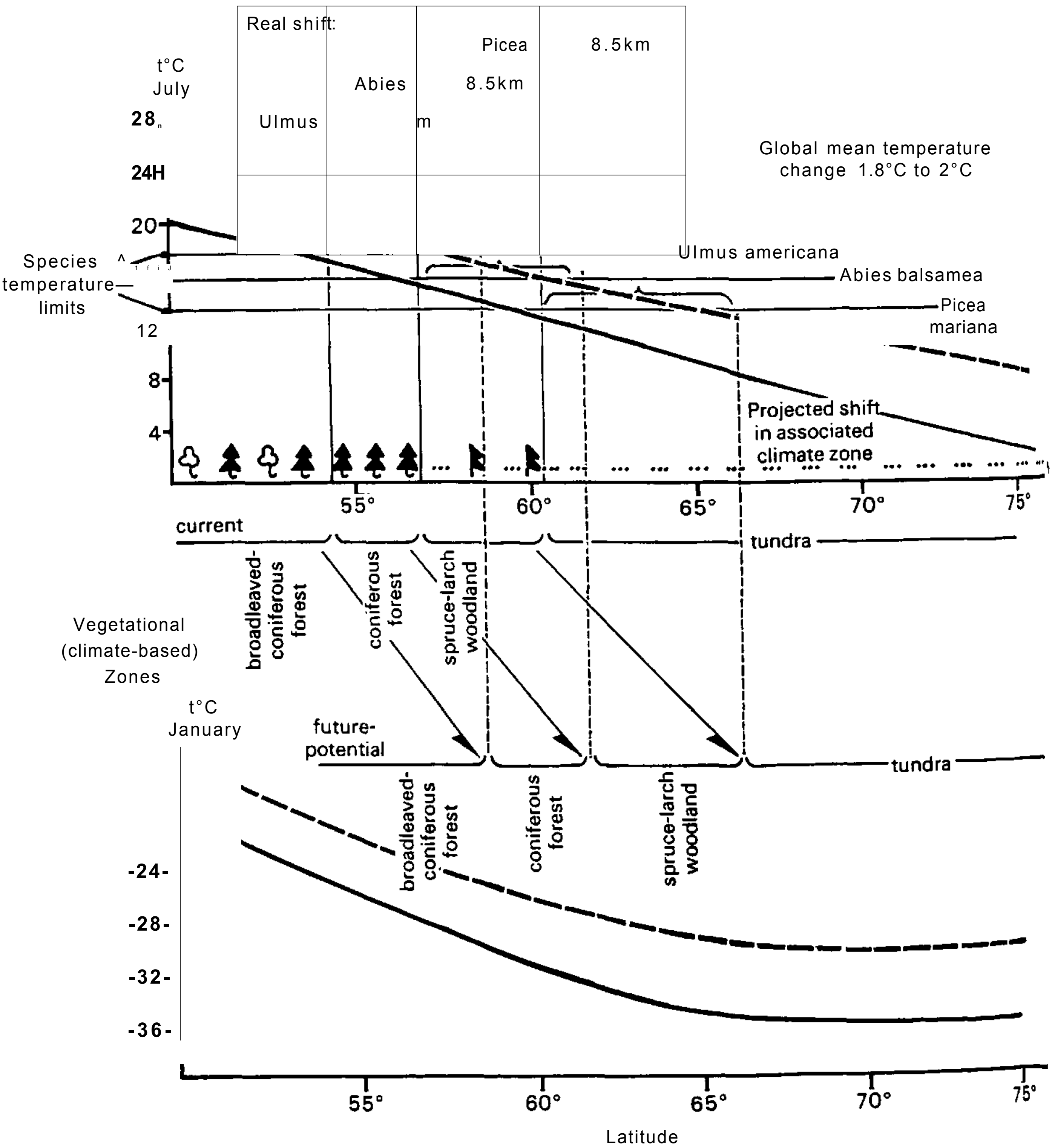


Figure 3.3b Potential changes in the distribution of the main tree species as a result of projected increases in temperature in Canada along a transect at 100 °W longitude (Velichko et al., 1990) - increase in global mean temperature of 1.8-2°C



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Chapter 4
Hydrology and water resources

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1 Introduction

Changes in climatic conditions due to increasing atmospheric concentrations of radiatively active trace gases will probably alter land and water resources, their distribution in space and time, the hydrologic cycle of water bodies, water quality, and water supply systems and requirements for water resources in different regions. Quantitative estimates of the hydrologic effects of climate change are essential for understanding and solving potential water resource problems associated with domestic water use, industry, power generation, agriculture, transportation, future water resources systems planning and management, and protection of the natural environment.

Climate change can be expected to lead to changes in soil moisture and water resources. The most important climate variable that may change is regional precipitation, which cannot be predicted well. Water supply and use in semi-arid lands are very sensitive to small changes in precipitation and evapotranspiration by vegetation, because the fraction of precipitation that runs off or percolates to groundwater is small. Increased heat will lead to more evapotranspiration, but the increase is expected to be partly offset by reduced plant water use in a COj-enriched atmosphere.

Higher temperatures may also have an impact in the transitional winter snow zones. More winter precipitation would be in the form of rain instead of snow, thereby increasing winter season runoff and decreasing spring and summer snowmelt flows. Where the additional winter runoff cannot be stored because of flood control considerations or lack of adequate storage, a loss in usable supply would be the result.

This chapter presents estimates of the influence of climatic change on hydrologic and water resource conditions in various countries and regions.

2 Climate scenarios

Forecasts of changes in climatic conditions for different regions and periods of time are required to estimate the hydrologic effects of increasing trace gas concentrations in the atmosphere. Air temperature, precipitation, cloud cover or insolation, wind speed and humidity are the most important conditions. However, reliable forecasts of regional climate change are unavailable. In their absence, various approaches to the development of scenarios of future climatic conditions are used, including (1) hypothetical (or prescribed) scenarios, **(2)** scenarios obtained from atmospheric general circulation models (GCM), and (3) scenarios based on historical and palaeoclimatic reconstructions.

The first approach is to prescribe climatic changes for various regions or river basins in a simplified manner. As a rule, such scenarios specify air temperature increases from 0.5 °C to 4.0 °C and precipitation changes (increase or decrease) in the range of 10% to 25%. Some authors also prescribe hypothetical changes in evaporation.

The second approach is to obtain scenarios directly from GCMs in which the atmospheric concentration of CO_2 is doubled (2 x CO_2). A problem with using GCMs is that the simulations for the same regions by different climate models may yield different and sometimes opposite results, especially for precipitation changes (Gleick, 1988).The third approach is to develop future climate analogs based on climatic reconstructions of past warm epochs, when atmospheric CO_2 was above the present value. For instance, Soviet climatologists show in their studies (Budyko and Izrael, 1987) that the so-called Holocene optimum (about 5-6 KA) can be considered as a 1°C global warming analog (about in the year 2000-2005); the last interglacial epoch (the Mikulino, 125 KA) can serve as an analog of the climatic conditions with a 2°C warming in the year 2020-2025; and the Pliocene climatic optimum that took place a few million years ago, with mean air temperatures 3°C-4°C above present, can be an analog of climatic conditions for the more distant future years 2040-2050.

There are difficulties and limitations in the application of palaeoclimatic reconstructions owing to the uncertainty of the climatic conditions of the remote past and to the lack of reliable palaeoclimatic data for many regions and countries. There is also a continuing discussion of the relative merits of the three approaches. In the absence of reliable predictions, the question of which scenario is best remains unanswered.

3 Some physical aspects of hydrology and water resources

3.1 Methodological approaches

During the past 10 years hydrologists from many countries have extensively studied hydrologic consequences of future anthropogenic climate change.

These studies are based on various methods that can be united into the following groups:

(i) Analysis of long-term variations in runoff and meteorological elements over past periods. This method can be approached in two ways. The first consists of statistical analyses of the relations between runoff, air temperature, and precipitation. This approach has been used by Stockton and Boggess (1979) and Revelle and Waggoner (1983) for western regions of the US and the Colorado River basin, and by Polyak and Speranskaya (1987) for annual river runoff in the USSR. The second way is to study the hydrologic consequences of past periods of very warm or cold, wet or dry conditions. Such analyses have been carried out by Schwarz (1977) and Glantz (1988) for the US, by Liu (1989) for northern China, and by Demaree and Nicolis (1990) for the Sahelian region.

In the US, the first major assessment of climate-runoff relations was conducted by Langbein et al. (1949), who produced a set of rainfall-runoff curves widely used in crude impact studies. These relations were tested and updated by Karl and Riebsame (1989), based on an analysis of actual climate fluctuations over 90 undisturbed drainages. They found that runoff was less sensitive to temperature changes than suggested by Langbein and his colleagues.

(ii) Use of water balance methods over a long period of time. In this approach the main task is to estimate future total evaporation. These methods have been used by Glantz and Wigley (1987) for the US, Babkin (Shiklomanov, 1988), Vinnikov et al. (1989) for the USSR, Griffiths (1989) for New Zealand.

(iii) Use of atmospheric GCMs. In this approach, GCMs with prescribed increases in the concentrations of trace gases in the atmosphere (usually 2 x CO_2) are used to obtain direct estimates of changes in the climatic and hydrologic characteristics for large regions. For example, possible changes in runoff, soil moisture, and evaporation have been estimated for the US and Canada using GCMs (USEPA, 1984; Sanderson and Wong, 1987; and Singh, 1987).

(iv) Use of deterministic hydrologic models. In this approach, rainfall-runoff models for river basins are employed with climatological data sets, including GCM outputs, to determine changes in hydrologic conditions. This approach was used by many authors for the basins located in various hydroclimatic environments (Nemec and Schaake, 1982; Gleick, 1986, 1987; Mather and Feddema, 1986; Cohen, 1986; Flashka et al, 1987; Bultot et al, 1988; Kuchment et al, 1989; Shiklomanov, 1989a; and Croley, in press).

The first and second methods have been widely applied to estimate changes in water resources over large areas because a relatively small amount of initial data is required, usually annual runoff, precipitation, and air temperature. Caution should be exercised in extrapolating regression relationships over past years to future periods. One cannot assume that a past interannual pattern of meteorological factors will be repeated in the future. It is also true that for the same annual precipitation and temperature, annual runoff can widely vary, depending on the distribution of the meteorological variables within months and seasons.

The results obtained in hydrologic simulations based on different GCMs are inconsistent for certain important hydrologic conditions and regions. This can be attributed to the low resolution of the current generation of GCMs, and to their simplified description of hydrologic processes. Nevertheless, the approach is very promising and studies of this type should be continued.

Deterministic hydrologic models have some desirable properties. They allow explicit study of causal relations in the climate-water resources system for estimating the sensitivity of river basins to changing climatic conditions. In addition, when regional climatic forecasts are available, possible runoff changes in different hydroclimatic environments may be simulated for water planning and management.

Perhaps the most comprehensive assessment of the effect of climate change on water resources was a recent report that focused on the US by the American Association for the Advancement of Science Panel on Climatic Variability, Climate Change and the Planning and Management of US Water Resources (Waggoner, 1990). This document includes 18 papers by more than two dozen authors and encompasses methods and issues ranging from climate forecasting, the translation of climatic change information into hydrologic consequences, vulnerability of water systems, impacts and responses, to future water use and decision making under climate uncertainty. Its contents cut across most of the above stated methods.

3.2 Changes in annual and seasonal conditions

Since the late 1970s, changes in annual and seasonal runoff have been extensively investigated and described in many publications. This is because annual and seasonal river runoff are very important for providing adequate water supplies to meet the demands of most regions. Quantitative estimates have been obtained for many regions of the US, for the USSR and New Zealand, for some regions of Canada, river basins in England, Wales, Belgium and other specific regions (see Sections 4 and 5).

Investigations highlight the great sensitivity of river watersheds to even small changes in climatic conditions. Watersheds located in arid and semi-arid regions are especially sensitive because annual runoff is highly variable. For watersheds where snowmelt is an important source of runoff, annual runoff and its seasonal distribution is vulnerable both to changing air temperature and to changing precipitation. In middle latitudes of the Northern Hemisphere with a 1°C or 2°C warming, the winter runoff is expected to increase drastically and spring high water to be lower owing to earlier snowmelt (see Section 4).

Many estimates of runoff change due to global climate warming, including those given in Sections 4 and 5 do not consider the possible direct influence of increased CO_2 on évapotranspiration (with increased CO_2 concentration évapotranspiration usually decreases). This phenomenon is considered in Idso and Brazel (1984) for five US river basins as well as in Aston (1987) for river basins in Australia. In these studies, the results were opposite to those obtained by other researchers, namely, a doubling of CO_2 concentration brought about a 40% to 60% increase in annual runoff for US rivers in question, and that for Australian rivers by 60% to 80%. Wigley and Jones (1985) and Palutikof (1987) pointed out to the great role of taking into account the direct CO_2 effects on évapotranspiration and total evaporation, which is ignored by many researchers. These findings are controversial and need further investigation as total evaporation from land is thought to be determined primarily by energy factors.

An important hydrologie consequence of global warming is potential changes in runoff extremes, both high and low. Changing high flow extremes raise the problems of runoff control, development of flood control works, and design of hydrologie structures. Changing low flow extremes may require a reassessment of water storage requirements and of water allocation schedules, in particular in the limiting periods of the year.

Estimation of extreme river runoff conditions in conjunction with anthropogenic climate change is a very important problem in hydrologie engineering calculations, since the design of hydrologie structures is based on the concept of stationarity of hydrometeorological conditions. It is assumed that the observational data over past decades reflect hydrometeorological conditions during the design life of the project. Changes in extremes will modify statistical calculations to estimate sizes of constructions and their conveying capacity and to maintain stability during disastrous natural events.

Since extreme meteorological events cannot be explicitly forecast by GCM simulations, nor by using palaeoclimatic analogs, in practice the quantitative regional estimates of possible changes in runoff extremes are as yet unavailable. Nevertheless, there are plenty of qualitative estimates, based usually on an assumption about the proportionality of changes in runoff extremes to those in annual, seasonal or monthly runoff (see Section 5). More reliable conclusions about the runoff extremes in various regions of the world could be drawn if detailed quantitative estimates of changes in meteorological characteristics over shorter periods of time were available.

3.3 Water demand

Under global climate wanning, changes in demand for water resources should be expected in many regions of the world. Considerable transformation in the structure and the character of water consumption by different branches of industry and agriculture, and deepening conflicts and contradictions between individual water users, are possible. With the same level of economic activities in a region, the water requirements and even actual consumption are determined by the extent of total moisture delivery to the region.

The relation between water consumption and available water is illustrated in Figure 4.1 which shows per capita water consumption in the year 2000 and a dryness index R_D/LP (where R_D is the radiation balance of a wet surface, P is the precipitation, and L is the latent heat of condensation). The greater the dryness index, the higher the specific water consumption. The relations depicted in Figure 4.1 are derived for large natural-economic regions of the world by estimating future water consumption in various countries up to the end of the century under stable climatic conditions (Shiklomanov and Markova, 1986; Shiklomanov, 1988, 1989b). Using these graphs and knowing possible changes in climatic parameters with global warming, it is easy to estimate approximate changes in total water demands in different world regions. GCM simulations with 2 x CO_2 in the atmosphere allow direct estimations to be made for regional changes in the dryness index; such estimates have been made for the US (Stakhiv and Lins, 1989).

The actual values of water consumption in various regions will depend on climatic factors, the extent of development of water-consuming sectors of national economies (primarily on irrigated lands), and on the limitations in water resources. With significant future climate change there will probably be problems in planning and locating future irrigated areas, industries with high water consumption, reservoirs, and problems of water supply for current water users. These changes may exacerbate problems in arid and semi-arid regions, where at present there are difficulties with water supply and where conflicts take place between various water consumers and managers.

Much is known about how water resource systems operate under climatic stress, and extrapolations of this knowledge will help us anticipate impacts on management and demand for water, and on protection afforded from floods and droughts in a changing climate (Fiering and Rogers, 1989; Stakhiv and Hanchey, 1989).

A useful literature has developed on water system sensitivity and adaptability to climate fluctuations. Fiering (1982) and Hashimoto et al. (1982) laid out criteria for assessing system sensitivity, including reliability, resiliency and vulnerability. Matalas and Fiering (1977) described an optimising approach to designing water systems with climate fluctuations in mind, and Novaky et al. (1985) offered a conceptual model of water system impact and response and created a matrix for assessing system sensitivity to climate change. Klemes (1985) synthesised the water system sensitivity literature, suggesting that the key concept is reliability - the long-term ability of a system to meet demand despite fluctuations in climate.

Peterson and Keller (1990) have evaluated the influence of temperature and precipitation changes on the irrigation requirements and the possibilities of developing future irrigated areas in arid regions of the western US. They came to the conclusion that a warming could exert an enormous effect on irrigation development in the region. By increasing temperature by 3°C and decreasing precipitation by 10%, cultivated areas in the western US could decrease by 30% and efforts would be required to improve efficiency of water use and to develop new freshwater supplies (Gleick, 1989).

Studies on the effects of effects of anthropogenic climatic changes on irrigation water consumption have been conducted by the Food and Agriculture Organization (FAO) along with the UK's Institute of Hydrology for the 3240 km^2 Malibamatsama Basin in Lesotho (South Africa) (Nemec, 1989; Institute of Hydrology, 1988). Future climate change simulations for this region have been accomplished using a GCM with doubling CO_2. The GCM data indicated a 6°C increase in mean monthly temperature, a 4-23% decrease in monthly precipitation from December to May, and a 10-15% increase in monthly precipitation from June to November. Estimates of changing evaporation and river runoff were based on a water-balance model with a 10-day time increment. The research showed that with a doubling of CO_2, changes in meteorological conditions in the Basin led to a 65% increase in water demands for irrigation; this could bring about the shrinkage of irrigated areas from 37,500 ha at present to 20,000 ha.

Regional estimates of potential changes in water demand with global warming are presented below in Sections 4 and 5. The cases indicate that estimating future water requirements and arrangements should be made by taking into account the peculiarities of each region. Then the reliability of such estimates will be primarily dependent on the accuracy and comprehensiveness of predicting the changes in climatic characteristics and hydrology with global warming.

3.4 Water balance and lake levels

The hydrologic cycle of large lakes, in particular of enclosed lakes, integrates climatic variability over vast areas, including the lake basins and adjacent regions. Future global warming due to increasing CO_2 in the atmosphere would lead to changes in the lake water balance components (precipitation, evaporation, inflow and outflow), their levels and heat budget. These changes are different for the drainage basins and the enclosed lakes. Given below in Section 5, as an example, are some approximate estimates of possible changes in the water balance and hydrologic cycle of the North American Great Lakes and of the Caspian Sea, the largest enclosed lake in the world.

3.5 Other hydrologic characteristics

The hydrologic consequences of anthropogenic global warming are not limited to changes in river runoff and water balance values. Other consequences include changes in total water amount and levels, erosion in river basins and riverbeds, and modifications of turbidity and sediment load. Water quality in many water bodies could deteriorate. Decreasing river runoff and lake level declines could decrease the possibility of dissolving pollutants and flushing processes.

Sea-level rise and runoff changes could lead to increased flooding of low-lying coastal regions, increased shoreline erosion, changes in deltaic processes, salinity changes in estuaries and rivers, and contamination of aquifers through saltwater intrusion (see Chapter 6). Answers to questions associated with the hydrologic consequences of global warming can be found only through innovative and geographically diverse studies that take into account forecasts of both changing regional climatic conditions and water use.

4 Hydrologic and water resource changes in large regions and countries

4.1 North America

4.1.1 United States

In the US, in the 1970s and 1980s, on the basis of hypothetical climate scenarios and river runoff dependence on meteorological factors, future annual runoff changes were determined for the northeast (Schwarz, 1977) and western regions of the US (Stockton and Boggess, 1979), and the Colorado River basin (Revelle and Waggoner, 1983). A similar study, using an annual water-balance model was conducted by Flaschka (1984) for the Great Basin rivers. A deterministic hydrological model was used by Nemec and Schaake (1982) to study two idealised basins in arid and humid regions. The research demonstrated a strong sensitivity of river basins (in particular, in arid and semi-arid regions) even to small changes in climatic conditions.

For example, increasing the annual air temperature by 1°C or 2°C and decreasing precipitation by 10% decreases the annual river runoff in regions with relatively low precipitation by 40% to 70%. Subsequently, these results were supported by calculations made by Stockton et al. (1989) who used more advanced models simulating runoff formation in river basins. These authors predict changes in water resources for diverse water supply regions of the country using two hypothetical scenarios: warm and dry (temperature change of +2°C, precipitation change of -10%) and cold and wet (-2°C and + 10%). The results are given in Figure 4.2. They show that for many regions of the US, water resources are expected to decrease by 1.5 to 2 times under the warm and dry scenario.

Schaake (1990) investigated how the sensitivity of runoff to given scenarios of climatic change would vary spatially with different climate conditions over the southeastern US. A simple, monthly, non-linear water-balance model was developed using a basin in China and another in Oklahoma, US. Constant values were assumed for the five parameters of the model over the entire region. The model and parameter values were tested using more than 2000 station-years of data from 52 basins in the region. None of the test data were used to develop or calibrate the model. Simulated mean annual runoff for 49 of the 52 basins fell within error bounds of 100%. The climate scenarios were for changes of 10% in potential évapotranspiration and 10% in precipitation. The study concluded that the hydrologic processes amplify the effects of such changes on runoff.

A measure of this amplification is elasticity; the ratio of the relative change in a runoff variable to the relative change in a climate variable. To illustrate this point, maps showing the percentage change in mean annual runoff to a 10% change in precipitation and potential évapotranspiration are presented in Figure 4.3. Elasticities as high as 5 were found in the southeastern US. The study concluded that: dry climates are more sensitive to change than humid climates; elasticity to precipitation change is greater than to évapotranspiration change; low flows will be more affected than high flows; reservoir yields will be affected, but the elasticity of reservoir yield is less than the elasticity of the mean flow; and, because water quality problems tend to be coupled with low flow conditions, water quality effects may prove to be among the most significant, especially in arid areas.In 1984, the US Environmental Protection Agency (USEPA, 1984) used output from GCMs directly for analysing changing precipitation, soil moisture, and runoff under doubled atmospheric CO_2 conditions. The results indicated a significant increase (20%-60%) in river runoff in the northwestern US, and a decrease (26%) in the central region. Manabe and Wetherald (1986) obtained similar results using a GCM to estimate soil moisture changes in the mid-continent region of the US. In contrast, however, simulations with other GCMs produced opposite results for the same region (Schlesinger and Mitchell, 1987; Mitchell and Warrilow, 1987).

Developing reliable scenarios of potential climatic changes for regional impact assessment is a major problem. The use of output from the current generation of GCMs to estimate regional hydrologic impacts of climatic change is highly suspect because of the coarse resolution of the models and the gross simplifications used in the parameterisations of the terrestrial hydrology (Gleick, 1989; WMO, 1987). Since soil moisture and river runoff processes are not well specified in GCMs, a more fruitful approach for estimating hydrologic impacts is the coupling of GCMs and deterministic hydrologic models. In this case, the GCM output (typically temperature and precipitation) becomes the input data for more comprehensive regional hydrologic models.

Gleick (1986,1987) was one of the first to apply this approach for estimating global warming effects on the seasonal runoff of the Sacramento River (California). As the basis, Gleick used climate change scenarios (monthly air temperature and precipitation) developed from three GCMs with 2 x CO_2 in the atmosphere. Simulation of hydrologic impacts was carried out with a water-balance basin model with a monthly time increment. These simulations showed increased winter runoff from 16% to 81% and decreased summer runoff from 30% to 68%. These results can be explained by a drastic change in snowfall and snowmelt conditions associated with a rising air temperature. A similar approach has been used by other authors. With doubling atmospheric CO_2, Great Lakes basin runoff decreased by 12-13% (Sanderson and Wong, 1987), Great Lakes net basin supplies decreased by 2-113% (Croley, in press), and the flow of large rivers in the Province of Quebec, Canada, increased by 7-20% (Singh, 1987).

Of the four GCMs most widely used in the United States, none is capable of simulating observed annual or seasonal precipitation with accuracy on a regional basis. The models also differ in the values of forecasted warming for US regions, particularly for the summer months. Nevertheless, in analysing the conclusions drawn by different researchers, the following regional tendencies are presented as potential hydrologic effects of global warming:

Pacific Northwest: some increase in annual runoff and floods;

California: a considerable increase in winter and decrease in summer runoff with insignificant rise in annual runoff;

Colorado and Rio Grande River Basins, the Great Basin: decreasing runoff;

Great Lakes Basin: decreasing runoff and increasing evaporation;

Great Plains, northern and southeastern states: uncertain changes in water resources.

The above inferences were also obtained by Soviet climatologists (Budyko and Izrael, 1987) using palaeoclimatic analogs. These results show a considerable decrease in moisture south of 55°N and a noticeable increase in precipitation in northern regions of North America.

4.1.2 Canada

In recent years a number of studies have investigated the potential hydrologic and water resources effects of a climatic warming for Canada over the coming decades. Most of these studies have based their impacts on climatic simulations produced by the GISS, GFDL, and UKMO GCMs (Marta, 1989). A summary of the results of these studies is presented in Table 4.1. Most of the investigations focused on one of three distinct areas in the south-central part of the nation: the Great Lakes, James Bay, and the Saskatchewan River sub-basin. A nationwide study of broad Canadian regions has also been completed. In the Great Lakes region, GCM-simulated temperatures range from +3.1°C - +4.8°C. The simulations for precipitation are much more variable, ranging from -3% to +8%. Generally speaking, the mix of this range of conditions could portend a decline in the hydrologic and water resource base or the region. Under these temperature and precipitation conditions, runoff to the lakes is estimated to decrease between 8% and 11%, lake levels could drop between 21 cm and 59 cm, and water supplies could fall from 18% to 21%.

Farther north, in the James Bay region, the water resource picture appears more favourable. Model-simulated temperature increases for this area fall in the range of 3.5°C to 4.7°C, with precipitation estimated more narrowly to increase from between 15% to 17.5%. This range of climatic conditions favours increases in runoff ranging from 8% to 16% with concomitant increases in water supply of 9% to 22%. Moving west onto the Canadian Prairie, impacts on the hydrology of the Saskatchewan River sub-basin appear to be strongly model-dependent. Both the GISS and GFDL simulations indicate impacts of fairly large magnitude, especially in terms of changes in the timing, location, duration and extent of runoff as well as soil moisture. However, the GISS simulations indicate increasing streamflows and water supplies for the region while the GFDL simulations indicate decreases. In terms of net basin supply, incorporating projected consumptive use, the GISS simulation produced a range of increases varying from 29% to 40%. On the other hand, the GFDL simulation produced declines in net basin supply ranging from 27% to 70% (Cohen et al, 1989).

Water in the Saskatchewan River sub-basin is utilised for agriculture, hydroelectric power production, cooling at thermal power plants, recreation and industrial processing. Agriculture is a major con

Table 4.1 Estimated hydrologic impacts of varying climatic change scenarios for Canada (Marta, 1989).

Author	Region	Drainage area (km² x 10⁴)	Est. climatic changes (T°C)	(P%)	(GCM)	Est. hydrological changes (Runoff - %)	Other
Southam and Dumont (1985)	Great Lakes	76.0 (32% is lake surface)	+4.5	-3 to +8	GISS/84		Levels (cm) -21 to -59 Flows (%) +2 to -13
Cohen (1986; 1987)	Great Lakes	76.0	+3.1 to 3.7 +4.3 to 4.8	+0.8 +6.5	GFDL/80 GISS/84	-8.2 -10.9	Supply (%) -18.4 Supply (%) -20.8
Singh (1988)	James Bay	17.5 (18% is lake and reservoir surface)	+3.5 +4.7	+17.5 +15	GFDL/80 GISS/84	+10.9 +15.7	Supply (%) +13.9 Supply (%) +16.1
Cohen et al. (1989)	Saskatchewan River	36.4	+2.5 +4.4	+18 +19	GFDL/80 GISS/84	-58 +37	Supply (%) -65 Supply (%) +38
Haas and Marta (1988)	S. Saskatchewan River (to Lake Diefenbaker)	15.7	+2.5 +4.4	+18 +19	GFDL/80 GISS/84	-20 +28	
Ripley (1987)	Arctic	331.0	+2 to 3.5	+54	UKMO/83	+95	
	Atlantic	151.0	+2 to 3.5	+11	UKMO/83	+10	
	Gulf	3.0	+2.5 to 3	+23	UKMO/83	+235	
	Hudson	356.0	+2 to 4.5	+17	UKMO/83	+20	
	Pacific	94.0	+2 to 3	+23	UKMO/83	+20	
	Canada	935.0	+2 to 3	+23	UKMO/83	+32	

sumer of water, in which return flows are considerably less than withdrawals from surface supplies.

Certain others, such as hydroelectric production and recreation, are in-stream users that do not 'consume' water, that is, their use of water does not result in a 'loss' from surface supplies. If the status quo is to be maintained, results from the study of this watershed indicate that for the GISS scenarios, an increase in agricultural demand for water would not significantly affect the availability of water for other users, since the net basin supply is estimated to be relatively high. For the GFDL scenarios, however, the low estimated net basin supply could seriously compromise all users. Such a situation would necessitate a major policy response, such as the establishment of a regional water allocation scheme for the sub-basin, involving government agencies, user groups and the public. Should there be increases in population, reservoir storage, industrial or agricultural development, such a scheme might not be required to cope with the conditions estimated under the GISS scenario, but any increases in water demand would only make the situation more critical given the conditions estimated by the GFDL GCM.

Looking very broadly at the impact of climatic warming on the water resources of Canada in the aggregate, the general outlook may be somewhat favourable. With temperature rises generally in the 2°C to 4°C range and precipitation generally increasing across the country from 11% to 54%, runoff could be expected to increase in all major regions by 10% to 235% (Ripley, 1987).

4.2 Brazil

The Brazilian government and scientific community only recently became concerned over the prospect of a greenhouse-gas-induced climate warming and its associated consequences on the water resources of South America. Attention has been given to the possible effects of deforestation of Amazonia on regional hydrology and atmospheric carbon dioxide. Very recently, the Brazilian government began to exert some control over the deforestation process.

Although this is a positive step toward decreasing the atmospheric build-up of CO_2, it is also necessary to point out that fossil fuel combustion is about 3 to 5 times more important than deforestation as a net contributor to global warming (Moore and Bohn, 1987).

As yet, there are no indications of a large scale anthropogenically-induced change on precipitation in the Brazilian Amazon (Sternberg, 1987). This stability is probably due to the relatively small percentage of the total rainforest area that has been deforested (7%). Nobre et al. (1989) simulated the climatic effects of total deforestation using a model developed by Sellers et al. (1986). This model incorporates the interactions between vegetation and the general circulation of the atmosphere. The model results indicated that the ground temperature in the Amazon region would increase between 1°-3°C, évapotranspiration would decrease 20-40%, and precipitation would decrease 20-30%.

Such a temperature increase, whether from deforestation, fossil fuel emissions, or both, will probably intensify and concentrate tropical convective rainfall and, as a result, promote increased flooding and erosion, and decreased soil moisture. This suggests that the firm yield from existing reservoirs could decrease and that the probability of dam overtopping owing to extreme floods may increase.

4.3 Western Europe and Scandinavia

Effects of climate change on water resources have been estimated for Western Europe (primarily for the northern regions) by using various scenarios and approaches. Western Europe was similar to North America in that river basins were very sensitive to small variations in climatic conditions, especially precipitation (Palutikof, 1987; Novaky, 1985; Beran, 1986; and Verhoog, 1987).

Studies by Schnell (1984) and Beran (1986) are significant for forecasting future water resources. Schnell estimated the consequences of CO_2 doubling for river runoff in the countries of the European Economic Community (EEC) using temperature and precipitation derived from the UK Meteorological Office (UKMO) GCM. The runoff values obtained by Schnell using waterbalance methods show possible significant increases in the north of Europe (the UK, The Netherlands, and Belgium) and decreases of similar significance in central and southern Europe.

A very comprehensive assessment of the potential water resources response to climate change for over 12 countries within the EEC has been conducted by da Cunha (1989). Detailed information about water resources and water availability for each country, coupled with the scenarios of climatic change simulated by GCMs for the EEC region, indicate that man-induced climatic change is likely to influence water resources differentially in different parts of the region. If the simulated GCM results turn out to be correct, then average precipitation values in the southern part of Spain, Portugal, and Greece can be expected to decrease, while increases can be expected throughout the rest of the EEC region. The model results also indicate a tendency for reduced precipitation variability in some of the northern parts of the region during the entire year, and for increased variability in Greece and southern Italy during the summer. Such changes in variability could mean that higher flood peaks are possible in parts of the UK, Germany, Denmark, and The Netherlands, while more severe droughts are possible in Greece and southern Italy. Thus, it is implied that a large part of the EEC region would benefit from what appear to be potentially favourable changes in climate, while a smaller part in the south would suffer unfavourable impacts.

The impacts of climate change on water resources have been classified by da Cunha into three groups: economic, social, and environmental. Economic impacts are often the most relevant. The changes in the global amount of water resources available and in the space and time distribution of these resources may lead to water shortages and cause water price increases. Changes in water quality are also likely as a result of climatic change. Temperature increases would also induce an increase in the demand for water, thus contributing to a worsening situation resulting from a decrease in water availability. The negative impacts are expected to be particularly serious on cultivated land areas. Examples of these negative impacts include crop losses or shortages, replacement of present agricultural species by other species more resistant to water shortage but less useful, increased activity of insects and predators, and the abandonment of agricultural land. Such impacts may also affect livestock by reducing herd sizes and increasing disease and problems of vector control. Other economic impacts relate to losses in timber production, fisheries, and recreational businesses. Important indirect impacts include sedimentation processes, ie erosion, transport and deposition of sediments, as well as agriculture, hydraulic work operations, and estuarine and coastal areas.

The social impacts of climatic change on water resources are also important, since it is essential that decision makers provide guidelines on the strategies to be adopted by water users to enable them to cope with climate change. In fact, the various types of water users (farmers, industrialists or domestic consumers) are not, by themselves, able to assume individually the most positive attitudes in order to reduce the negative impacts of climate change on water resources. The possible climatic impacts on water resources will force society to modify its relation with the environment by introducing a number of adjustments in its behaviour. Emigration from the southern parts of the EEC unfavourably affected by climatic change would be one immediate form of social adjustment. Other possible social consequences include unemployment, deterioration of conditions of hygiene and public health in the affected regions, as well as public safety from forest fires.

Environmental impacts may also be relevant, ranging from serious ecological disruption to less serious and more localised effects. Examples of serious disruptions are desertification, which is a possibility in the southern region, and sea-level rise with possible effects on flooding in coastal areas, destruction of engineering works and structures, and modification of coastal and estuarine environments. Examples of more localised effects include damage to wildlife habitat owing to water shortages, degradation of visual landscape quality, increased salinity of soil and groundwater, soil, erosion, forest fires, plant diseases, and insect and predator plagues.

Bultot et al. (1988, 1989) made the most detailed estimations of river runoff changes for Belgium with a doubling of the CO_2 concentration. The authors used the monthly values of climatic conditions obtained from GCMs predicting a 2.9 °C annual air temperature increase and a 55 cm precipitation rise. To assess the hydrologic consequences for the three river basins with different conditions of runoff formation, a conceptual hydrologic model with diurnal time increments was used. The calculations showed increasing annual runoff (3-10%) and changes in the seasonal runoff pattern. The winter and spring runoff increased by 10-14%, while the summer runoff remained unchanged of decreased from 1% to 15%).

To date there have been no studies in the UK using hydrologic models to estimate the effect of climatic change on annual runoff. Beran and Arnell suggest, however, that it may be possible to make some generalised statements using a simple water-balance approach where changes in mean annual runoff are determined from changes in mean annual rainfall and mean annual evaporation (Beran and Arnell, 1989). Evaporation, however, is dependent on several climatic attributes which vary together in a complex manner. Thus, a simple empirical formula developed by Turc (1954), which operates on an annual time scale, was utilised by the British.

Mean annual runoff is estimated by subtracting evaporation from precipitation, for three combinations of mean annual temperature and precipitation found in different parts of the UK (Table 4.2). Parts a and b in the table represent catchments with similar rainfall, but different mean annual temperature and, for a given change in precipitation, there is relatively little difference in effect on runoff between the 'cool Scottish' and 'mild English' sites. The data in the table imply that if temperatures were to increase by 3°C, an increase in annual precipitation of 10% or more would lead to an increase in annual runoff. For comparative purposes, the current scenario implies an increase in annual rainfall of 140 mm (14% on an initial value of 1000 mm) if summers are wetter (as in Scotland and the north of England), but only 80 mm (8%) if summers are drier. The estimated conditions depicted in part c of Table 4.2 are more representative of the drier climates of southern and eastern England. Here annual precipitation would have to increase by over 10% before annual runoff would increase. The scenario increase in precipitation of 80 mm (10% of 800 mm) is just at this threshold value.

These estimates imply that mean annual runoff would probably increase over most of the UK in a warmer world, with the greatest increase in the north. The actual increase in runoff is very sensitive to the estimated increase in precipitation (more so than to changes in évapotranspiration). It is important to note that alterations in annual runoff due to climatic change may approach changes in runoff due to major land use change. Gross et al. (1989) used a conceptual rainfall-runoff model to show, for example, that clearing the forest in a small basin in upland Wales could produce an increase in annual runoff of nearly 30%.

Although the evidence is limited, it is possible that the model-simulated increased seasonality in rainfall will be reflected in a stronger seasonal variation in streamflow throughout the UK. Note, even under the 'wet summer' scenario, increases in summer precipitation are less than increases in winter precipitation. However, the effect will depend strongly on catchment geology, and it is possible that summer flows in catchments with high groundwater levels will be maintained or even increased by higher winter and spring rainfalls.

Saelthun et al. (1990) have produced an initial assessment of the consequences of climatic change for water resources in Norway. Using a climate

Table 4.2 Extimated percentage changes in mean annual runoff at three sites in Great Britain in response to changes in temperature and precipitation*

a) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 8 °C
Initial estimated mean annual runoff: 530 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-21.3	-4.8	12.3	29.7	47.4	65.3
2	-25.8	-9.6	7.1	24.2	41.7	59.4
3	-30.4	-14.7	1.7	18.5	35.8	53.3
4	-35.1	-19.8	-3.8	12.7	29.6	46.8
5	-39.8	-25.0	-9.5	6.6	23.2	40.1

b) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 479 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-23.0	-5.6	12.6	31.2	50.2	69.6
2	-28.1	-11.2	6.4	24.7	43.4	62.5
3	-33.3	-17.0	0.2	18.0	36.3	55.1
4	-38.5	-22.8	-6.2	11.1	29.0	47.4
5	-43.7	-28.7	-12.7	4.1	21.5	39.5

c) Initial mean annual precipitation: 800 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 311 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-26.1	-7.0	13.3	34.4	56.3	78.8
2	-32.2	-14.0	5.5	26.0	47.3	69.3
3	-38.3	-20.9	-2.3	17.4	38.1	59.5
4	-44.2	-27.8	-10.1	8.9	28.8	49.5
5	-49.9	-34.6	-17.8	0.3	19.4	39.4

* Based on the Turc formula (Beran and Arnell, 1989)

change scenario of a temperature increase of 1.5°-3.5°C (with the higher temperatures prevailing during winter and in upland areas) and a precipitation increase of 7-8%, the following hydrologic consequences were posited. Annual runoff in mountainous areas and regions of high annual precipitation will likely experience a moderate increase. In lowland and forest inland basins, annual runoff may decrease in response to increased evapotranspiration. The intensity of the spring flood could decrease in most basins, while winter runoff may increase substantially and summer runoff may decrease. Floods are likely to occur more frequently in autumn and winter. The period of snow cover will probably be shortened by one to three months. The scenarios indicate that glaciers will decrease, particularly those in inland areas. The net melt could be lower on glaciers near the west coast, while the glaciers on the coast of northern Norway will most likely remain unchanged. The duration of ice cover may decrease and it is possible that many of the larger lakes in southern Norway may not develop ice covers in most winters.

Erosion and sediment transport is likely to increase significantly during winter unless the agricultural practice of leaving soils bare during winter is changed. Soil loss could become a very serious problem.

Finally, a positive potential outcome of global warming is that the hydroelectric power production of Norway could increase by 2-3% under the assumed climate change scenario. This is due in part to an increase in reservoir inflows, and in part to reductions in reservoirs spillovers. The seasonal distribution of runoff may more closely match that of energy consumption, thereby increasing firm power yield.

4.4 Union of Soviet Socialist Republics

Quantitative estimates of potential climate change effects on rivers in the USSR have generally been based on palaeoclimatic analogs of the past. The proxy-based estimates were first obtained at the State Hydrological Institute in 1978 under the guidance of M.I. Budyko (Budyko et al, 1978). Subsequently, as the climatic predictions were refined, estimates were made for changes in annual runoff of rivers in the USSR for the years 1990, 2000, and 2020. This procedure was repeated for other regions of the Northern Hemisphere. The results of these simulations are presented in the report Anthropogenic Climatic Changes (Budyko and Izrael, 1987) and by Shiklomanov (1988). The simulations were based on meteorological-runoff relationships, or on water-balance equations, developed over long time periods. The results of the simulations were presented in the form of runoff change isoclines and also as averages for the main basins for the years 2000-2005. These average changes were in the range of +/-12% (Shiklomanov, 1988). The values are only rough approximations due to the uncertainty associated with the initial air temperature and precipitation data for certain river basins.

The mean annual runoff changes over the USSR for a 1°C global warming (expected to occur between 2000-2010) have been estimated. This work was based on refined predictions of changes in summer and winter temperature and annual precipitation for the USSR (Budyko, 1988) developed at the State Hydrological Institute under the guidance of K.Ya. Vinnikov. The comprehensive data presented in Figure 4.4 suggest the following conclusions. The most detrimental effect on resources can be expected in the south of the forest zones of the European USSR and west Siberia. Annual runoff could fall to 10-20% of normal (20-25 mm). This effect is due to an increase in air temperature accompanied by no change or even a slight decrease in precipitation.

In the southernmost steppe regions, owing to a marked increase in precipitation, the annual runoff is most likely to increase by 10-20%. In the northern regions of the European USSR and Siberia, runoff may increase by 280-320 km^3/yr or 7%, which may compensate for future water consumption. Estimates for the more distant future are less certain; nevertheless, there is evidence to suggest that with a 2°C global warming the annual runoff will increase by 10-20% on all the large rivers of the USSR. This increase will provide an additional 700-800 km^3/yr of water for the whole country. Although these values are very approximate, they cannot be ignored in the long-range planning and management of water resources and protection of the natural environment.

Additional effects may be caused by global warming on seasonal and inter-annual runoff patterns. For a number of river basins in the European USSR, the influence of climatic change on the hydrologic cycle has been simulated using a specially developed water-balance model with a 10-day time increment. The model was calibrated and checked by observational data over long-term periods. The simulations were carried out for four river basins: one small and two middle-sized basins located in the forest-steppe and steppe zones, and the Volga River Basin, the largest in Europe. The climatic scenarios used included changes in summer and winter air temperature and annual precipitation in the years 2000-2005, taken from the palaeoclimatic maps for each river basin (increasing summer temperatures by 0.5°-1.5°C and winter temperatures by 1.5°-2.5°C and changing annual precipitation by -3% to +12%).

The model calculations show that even small changes in climatic conditions can lead to considerable alterations in the runoff regime. The primary manifestation of such an alteration is a dramatic increase in winter runoff, owing to more intense snowmelt during the winter season and a corresponding decrease in spring runoff. The seasonal runoff changes averaged over a long-term period for the indicated river basins are presented in Table 4.3. This table indicates that winter runoff for the relatively dry zone (steppe) increases many-fold and considerably rises even for the vast Volga River basin. Observational data show, on the rivers of the European USSR since the second half of the 1980s, that winter runoff has tended to increase noticeably, possibly as a consequence of global climate warming.

4.5 Northern China

The analysis of hydrometeorological observational data for northern China (Chunzhen, 1989) shows that the warmest period over the last 250 years began in 1981. The mean air temperature over the period 1981-87 was 0.5°C above the normal, while for the same period precipitation was somewhat lower than normal (for Beijing by 4%). Studies of natural climate variations for the past 100 years suggest that the warming in northern China will continue up to the next century. Estimates of the potential influence of increasing atmospheric CO_2 on northern China arc not available. At the same time, it is possible that small climate changes can have considerable hydrologic consequences. Simulations using the Hinangchzang hydrological model show that in semi-arid regions, with a 10% increase in precipitation and a 4% decrease in evaporation,

Table 4.3 Potential changes in seasonal runoff in response to a temperature warming of 1°C for selected rivers in the USSR

River	Basin area (km^2)	Zone	Runoff (mm)			
			Annual	Winter	Spring	Summer-Fall
Volga-Volgograd	1,360,000	Forest/Forest-steppe	187	22	107	58
			165	35	94	36
Sonsa-Yeletz	16,300	Forest-steppe	144	30	102	12
			129	53	63	13
Chir-Oblivskoye	8,470	Steppe	47	3	43	1
			70	22	45	3
Devitza-Nizhnedeyitsk	76	Forest-steppe	127	26	60	41
			112	36	41	35

Note: For each river the top set of runoff values refers to the long-term mean under natural conditions. The bottom set of values is the estimated runoff for an assumed warming of 1°C.

the runoff will increase by 27%. Increasing precipitation by 10% and evaporation by 4% results in an 18% increase in runoff. If these climatic changes take place in semi-arid regions, runoff increases by 30%-50% (Chunzhen, 1989).

4.6 Japan

A number of agencies and institutes within Japan have begun to focus on how climate warming would affect the water resources and related environment systems of that country. To date, the studies have emphasised the empirical description and characterisation of effects and problem areas with the aim of identifying how to derive quantitative estimates of likely impacts. To estimate the potential hydrologic consequences of global warming, long-term series of meteorological observations in different regions of the country have been analysed. In particular, precipitation and runoff characteristics have been compared over the coldest and the warmest 10-year periods with the mean temperature difference of 0.074°C. Precipitation over the warmest period turned out to increase by 10%, the incidence of heavy rains (more than 300 mm for two days) becoming much more frequent. At the same time, precipitation sums for 60- to 90-day periods with minimum rains during the warm decade have been noticeably smaller than in the cold decade (Yamada, 1989). This empirical data analysis makes it possible to assume that with global warming in most regions of Japan, maximum precipitation and river runoff volume are expected to somewhat grow, especially over the periods of rain storms. At the same time, in dry seasons the runoff can decrease thus exacerbating the problems of water supply. Because of the lack of data, it is impossible to estimate quantitatively the corresponding values. The use of GCM output is particularly troublesome in Japan since a large percentage of precipitation is generated by typhoons and convective storms, which are not resolved by the GCMs, as well as by frontal storms, which are. Accurate accounting of water resource impacts would, therefore, need to consider, for example, how typhoon frequency, magnitude, and intensity would be affected.

Given the critical concern with which the government of Japan views the potential threat imposed by a greenhouse-gas-induced climatic warming, a preliminary study was undertaken with the support of the Japanese Environment Agency (Matsuo et al., 1989). It assessed effects on a number of environmental systems, including water resources, associated with a potential severe change in climatic conditions. The specific water resources issues addressed included flood control, water use, and water quality.

Looking first at flood control, the report notes that current reservoir storage capacity is limited, so much so that the multipurpose use of reservoirs for flood control and water use could become increasingly difficult. An increase in rainfall intensity brought by typhoons or fronts would give rise to serious flooding. Prolonged periods of drought, punctuated by short bursts of intense precipitation, could lead to increased frequency of mudslides. Since many Japanese cities are situated in coastal areas and lowlands, any flood could produce heavy damages. Rising atmospheric temperatures could be expected to alter the timing and volume of snowmelt generated runoff, thereby producing the potential for increases in flood peaks and associated damages.

In terms of water use, a number of effects were identified. In general, water demand is expected to increase, while water supply decreases, spreading localised water shortages to broader regions or to the nation as a whole. Reduced precipitation and the associated reduction in discharge can be expected to reduce both the amount and regularity of hydroelectric power generation. In the particular case of rivers dependent upon snowmelt, the impact could be quite significant. Moreover, contamination due to salt-water intrusion could lead to acute agricultural and municipal water supply problems. Reduced water levels in rivers and lakes could also produce deleterious effects on navigation and recreational activities. Finally, with respect to water quality, the expectation is that river water quality will decline with decreases in minimum flow. Lake quality could be threatened by a prolonged state of thermal stratification, and increasing temperatures may lead to increased eutrophication. It is also thought that declines in the water level and storage capacity of lakes and dams could adversely affect water quality, although the precise mechanism behind such deterioration remains unclear.

4.7 New Zealand

In June, 1988, the New Zealand government instituted a national climate change program under the coordination of the Ministry for the Environment. Three working groups were formed, considering respectively facts, impacts, and responses, consistent with the three working groups of the IPCC. The Facts Working Group was formed to produce a report on the scientific basis for the predictions of climate change. An abridged version of this report has been published which contains the following conclusions (Salinger and Hicks, 1989). Annual average warming in New Zealand under a doubled CO_2 climatic regime range from 1.4°C to 3.5°C. There is some possibility that winter temperatures will rise faster than summer temperatures in more southerly parts of the country. It is possible that the snowline could retreat between 100 m and 150 m for every 1°C rise in temperature. However, even though New Zealand temperatures have increased by 0.5°C since the 1940s, no retreat of snowline or advance of tree line has yet been measured.

The Impacts Working Group was formed to produce a series of reports addressing the broad range of physical, biological, economic, and social issues likely to be affected by the climatic change estimates provided by the Facts Working Group. One of these impact reports deals with water resources (Griffiths, 1989). All the impact assessments considered two scenarios of climate change, one based on a temporal analog (referred to as SI) and the other on the limiting conditions simulated by GCMs (S2). The analog scenario is based on the period of maximum warmth 8,000 to 10,000 years ago, when westerlies were weaker and there was more airflow from the northwest. New Zealand temperatures were 1.5°C warmer than at present and westerly winds were lighter, especially in winter. There was a reduced frequency of frontal storms, and global sea-level was 20 cm to 40 cm higher than at present.

The second scenario is based on the model-simulated upper limit to greenhouse warming in the New Zealand area of 3°C. It is accompanied by positive mode Southern Oscillation conditions (La Nina) on average. Frequent incursions of tropical air from the north are expected and, although the intensity of the westerlies may decrease, they will still prevail. Moreover, global sea-level may be 30 cm to 60 cm higher than at present.

Regionally, the principal likely impacts of climate change on runoff are depicted in Figure 4.5, and more broadly on water resources as follows. In Northland, flooding could become more frequent and more severe. Baseflows in rivers and streams may be enhanced, while lake levels may rise. There could be greater groundwater recharge and less demand for irrigation. Wetlands may not drain as easily, especially in the Ruawai flats south of Dargaville. Earthflow and other erosion in weathered greywackes, Tangihia volcanics and podsolised sand hill country may precipitate increased suspended sediment loadings in rivers and streams.

A number of similar effects could probably occur in the region around Auckland. These include more frequent and severe flooding, enhanced baseflows in rivers and streams and increased lake levels, and greater recharge of groundwater and less demand for irrigation. There could also be changes in lake stratification patterns and a rise in the number of dune lakes. Moreover, a number of urban-related problems are possible. It may be that more care will be needed in siting urban developments to protect them from increased flooding. High intensity rainfalls may overload stormwater/sewerage systems leading to frequent discharges of contaminated water. Finally, the possibility of increased erosion may result in higher suspended sediment concentrations in estuarine and harbour receiving waters.

The region encompassing Waikato Bay of Plenty-Taupo also is likely to be more prone to frequent and sever flooding, especially in the Hauraki Plains, Bay of Plenty coastal plains, and Lower Waikato River valley. Enhanced baseflows in rivers and streams and lake levels on the volcanic plateau will rise. Lakes may stratify more often and a reduction in lake carrying capacity could possibly occur, although this may be offset to some extent by increased flushing rates and higher water levels. Anoxic conditions are likely in some lakes, while those already anoxic will probably have the period extended. This area, too, may experience greater groundwater recharge and reduced demand for irrigation. The increased frequency of subtropical cyclones may be compensated for by the lower frequency of southeasterly storms under climate scenario SI, but not under scenario S2. A number of other unique impacts are also likely. For example, geothermal systems may receive greater groundwater recharge; Waitomo Glow Worm Cave may be closed more frequently because of flooding, and siltation in the cave may increase; a significant increase in water yield from *Pinus* rodiafa-forested basins can be expected with more yield in summer than in winter; the operation of the Huntley thermal power station may be affected by increased river temperatures (discharges are already limited by temperature restrictions in the summer), although increased river flows may compensate to some degree; and sever gullying could occur in highly erodible volcanic materials leading to increased infilling of hydro-dam reservoirs, thus reducing reservoir life and flood storage capacity.

In the Taranaki-Manawatu-Wellington region flooding is also likely to become more frequent and severe, especially around Ohura, along with enhanced baseflows in rivers and streams. This area may experience a slight increase in groundwater availability and less need for irrigation under scenario SI and greater irrigation demand under S2. An increase in high intensity rainfalls will probably have significant effects on agricultural productivity in Taranaki, as well as overloading storm water/sewerage systems that could produce frequent discharges of contaminated waters. Increased erosion here will also probably result in higher suspended sediment concentrations in rivers and streams.

The southeast part of the North Island, the Gisborne-Hawkes Bay-Wairarapa region may exhibit a number of unique water resources effects. For example, greater incidence of drought and the more frequent drying-up of long reaches of river may accompany climatic warming, as well as diminished baseflows in rivers and streams in Hawkes Bay and eastern Wairarapa. Lake levels will be low more often and anoxic conditions could result at times, especially in Lake Tutira, while impedance of drainage at river mouths will occur in Hawkes Bay requiring increased pumping capacity. Although little change in groundwater recharge is likely, the increased use of groundwater for irrigation is. Also, under scenario S2, it is possible that devastating impacts could be produced by the more frequent passage of large tropical cyclones.

On the South Island, in the Nelson-Marlborough Region, the likely impacts include more frequent and severe flooding along with a small increase in the pumping of drains; urban flooding of east coast catchments; flooding in Tikaki Valley; enhanced baseflows; more droughts in the drier eastern hill country of Marlborough; and more frequent erosion episodes in the Marlborough Sounds. In addition, there may be a small beneficial effect in the availability of groundwater resources, and the Takaka River may run dry less often. However, salinity increases in the Waikoropupu Springs are possible, along with a slight increase in mean discharge, and highly erodible basins in eastern Marlborough could supply more suspended sediment to the Wairau River. This may affect irrigation regimes and produce an increased demand for groundwater.

Potential impacts in the Westland-Fiordland region include several that are more related to mountainous conditions. For example, the meltdown of the snowpack could significantly increase the size of flood peaks, while the drying out of regolith could promote slope failure during high intensity rainfalls giving increased suspended sediment loading in streams. Moreover, under scenario S2, there maybe an overall tendency toward a more stable, less extreme environment, but periods of water deficit are likely to occur.

In Canterbury, little change in groundwater recharge is likely under either scenario SI or S2, but an increase in the number of days of soil moisture being below the wilting point suggests that there may be greater demands for groundwater-supplied irrigation. There may also be a greater incidence of drought and of river reaches drying up, along with major aridity problems on non-irrigated downland areas. Canterbury will also probably experience greatly increased competition for water between instream and out-of-stream uses. Another potential problem relates to snowmelt. It is probable that there will be less water in rivers in late spring and early summer in those regions where snowmelt is now important. Moreover, very little snow storage is likely in South Canterbury resulting in significant changes in the temporal pattern of runoff. Snowmelt contributions will probably move forward about a month in time.

Finally, in the Otago-Southland region, a significant reduction in the long-term availability of groundwater is likely in the eastern parts of the regions. Droughts are likely to increase and major aridity problems may prevail in downland areas particularly in central and eastern regions. Eastern areas may also experience a greater and an earlier demand for irrigation water, while forested areas there will supply a reduced water surplus to stream flows and groundwater recharge. There is also likely to be increased water use by permanent grassland and a shortening of the period of soil water recharge.

5 Case studies of effects in critical or sensitive environments

5.1 Large water bodies

5.1.1 The Great Lakes Basin (US/Canada)

A detailed examination of available water supply and users for the Great Lakes basin reveals a number of commonly encountered conflicts among competing water uses, even under present climatic conditions. First, it should be recognised that there are two major and different hydrologic regions: the Great Lakes proper and the tributary watersheds. Most of the salient conflicting water uses for which the regulation and stabilisation of the Great Lakes is important is navigation and hydroelectric power production, which favour high lake levels versus recreation, reduction of flooding and shoreline erosion which favours low lake levels. The former (hydroelectric power and navigation) affects the basis of an extensive industrial economy in the region, while the latter affects millions of residents who wish to recreate on the shores of the Great Lakes and whose houses and property are affected by storm damage. Since the lakes themselves are a vast reservoir of water, the projected typical consumptive uses of water (municipal and industrial water supply, thermal cooling) are not expected to impose a significant incremental adverse impact. Tributary watersheds, on the other hand, experience highly variable flows, with significant present constraints on in-stream and off-stream water uses.

Over 8,000 km^3, storing 20% of the world's fresh surface water and 95% of the fresh surface water of the US, the Great Lakes have a surface area of 246,000 km^2. The drainage area, including the surface area of the Great Lakes encompasses nearly 766,000 km^2. Eight states of the US and two provinces of Canada (Ontario and Quebec) border the Great Lakes (Figure 4.6). Two of the Great Lakes are regulated: Lake Superior and Lake Ontario; ie their outflows are controlled. Lakes Michigan and Huron are connected by the Straits of Mackinac and their surface water elevations respond synchronously to changes in water supply.

The Great Lakes Basin encompasses a population of 29 million Americans (12% of the US population) and 8 million Canadians (27% of the Canadian population) (Cohen et al, 1989). Millions of people benefit directly from the water-resources related-services of the Great Lakes in the form of hydroelectric power, navigation/transportation of mineral resources including coal and iron and food. In 1975 economic activity in the US portion amounted to $155 billion (1971) while that of Canada was estimated to $27 billion (1971) (International Joint Commission, 1985). By 1985, the Great Lakes Basin accounted for 37% of the US manufacturing output, consisting of transportation equipment, machinery, primary metals, fabricated metals and food and beverage products.

The Great Lakes water levels have fluctuated over a range of 2 m during the past 150 years. Seasonal lake level variations average 0.3 m in Lake Erie and 0.5 m in Lake Ontario. Also, the Great Lakes region has experienced twelve serious droughts in the past 60 years and six periods of extensive flooding. A high precipitation regime during the past 20 years resulted in 1986 in record high lake levels for this century.

The GCMs used to predict temperature and precipitation differ substantially in their prediction for each of the regions under consideration. Figure 4.7 shows, for example, that the GISS model predicts a net increase in summer precipitation in the Great Lakes of about 0.4 mm/day, whereas the GFDL model shows a decrease of over 0.6 mm/day and the OSU model shows no change. Precipitation is important for non-irrigated agriculture (dryland farming). However, water availability in the streams (runoff) and in the soil is a function of évapotranspiration, which is a non-linear function of temperature. Hence, runoff computation based on GCM model outputs will also vary widely depending on the temperature and precipitation conditions predicted by each model. A comparison of the runoff computations for the doubled-CO_2 scenario based on the outputs of three GCMs (GISS, GFDL and OSU) was conducted by Croley (in press). The analysis used daily models to simulate moisture storage and runoff for 121 watersheds draining into the Great Lakes, over-lake precipitation into each lake, and the heat storage and evaporation for each lake. Table 4.4 shows that there is a 23% to 51% reduction in net basin supplies to all the Great Lakes for the three models. The largest changes in net basin supply would occur in Lake Erie, a feature that was uniform in all three models, with the GISS model showing the greatest percentage change. Sanderson (1989) simulated the effects that the reduction of net basin supply would have on the historical levels of Lake Erie from 1900-1980 (Figure 4.8).

Table 4.4 Estimated percentage changes in Great Lakes net basin supplies between current climatic conditions* and doubled CO_2 conditions**

	$1xCO_2$ Net basin supply and $2xCO_2$ relative changes			
Basin	**BASE (mm)**	**GISS (%)**	**GDFL (%)**	**OSU (%)**
Superior	847	-2	-57	-19
Michigan	698	-45	-65	-32
Huron	1052	-46	-41	-19
St.Clair	4395	-50	-28	-25
Erie	592	-113	-91	-56
Ontario	1941	-43	-29	-11

* (1 x CO_2 or the BASE case)

** as simulated by the GISS, GFDL and OSU GCMs (Croley, undated)

Thermoelectric power cooling is projected to increase significantly, accounting also for much of the increase in consumptive water use. Consumptive uses of water, largely through evaporation, represent a net loss of water to the hydrologic system. This fairly large loss was estimated by the USGS to be 85 cm in 1985, rising to 170 cm in 2000. This loss, however, would only account for a reduction of a few centimetres in lake levels in comparison to a one-half metre drop in lake levels projected from a reduction of net basin supplies due to increased natural evapotranspiration. If the dramatic climate change scenario were to materialise, the large socioeconomic impacts would stem from water use conflicts and shortages that are currently encountered primarily during naturally fluctuating low lake level stands. That is, hydroelectric power production would be significantly affected, particularly in the Lake Ontario and Lake Erie drainage areas. There are substitutes for the loss of hydroelectric power, but most will add to the emission of greenhouse gases (GHG) and consumption of thermoelectric cooling water.

Commercial navigation is a very important component of the Great Lakes economy that would be seriously affected by lower lake levels. Either cargoes would have to decrease to get through the locks, imposing increased transportation costs, or the locks on the Great Lakes would have to be rebuilt. In either case, the economic cost would be high.

The water resources impacts are also likely to be of great socioeconomic consequence in the streams of the watersheds that drain into the Great Lakes. These watersheds are largely unregulated and the municipalities and industries depend on natural streamflow and groundwater. Although the variability of weather and associated shifts in the frequency and magnitude of climate events were not available from the outputs of the GCMs, there is reason to believe that the increased precipitation regime predicted by some of the GCMs will result in greater and more frequent flooding in the tributary watersheds. Along with this trend, it is possible that the frequency, duration and magnitude of droughts might also increase as a consequence of the warming trend. In other words, the cycles of floods and droughts experienced in the current hydrologic record could become worse, exacerbating future conditions of higher water demands.

5.1.2 The Caspian Sea

The Caspian Sea is the world's largest enclosed lake with a surface area of 371,000 km^2. Lake-level variations have a very large amplitude and depend mainly on the river inflow-water surface evaporation ratio (precipitation on the lake surface is small). Over the last 2000 years the amplitude of lake-level variation has been about 10 m. Instrumental observations (since 1837) indicate that lake-level variations ranged between -25.5 m and -26.5 m abs during the period 1837 to 1932. The lake then began to fall and reached a low of -29.10 m abs in 1977. From 1978 to present the lake level has increased, reaching a level of -27.7 m in 1989 (Shiklomanov, 1988).

Future lake levels depend on natural inflow variation (80% of the inflow is contributed by runoff from the Volga River). Other controlling factors are man's activities in the river basin, anthropogenic climate changes, and changes in precipitation and evaporation. To assess future levels of the Caspian Sea, methods for probabilistic prediction have been developed which take into account potential effects of natural and anthropogenic factors, including global warming. The methods are based on a complex water balance model which uses Monte Carlo procedures to simulate an annual inflow series.

The scenarios were based on empirical data for all the water-balance components obtained since 1880. The mean decrease in river water inflow due to present and projected man's activities are, according to SHI estimates (in $km^3\ yr^{-1}$): in 1989, -40; 2000, -55; 2010, -60; 2020, -65. For every year the values of river runoff were taken separately for all the main rivers. In the case of non-stable climatic conditions, possible climate changes for the years 2000 and 2020 have been estimated for the basin and the Sea according to predictions by Soviet climatologists on the basis of palaeoclimatic reconstructions (see Section 4.4). Possible changes in river water inflow to the Sea have been obtained independently by two extreme estimates derived from the river runoff change maps for 2000 (Figure 4.9) and by the water balance model over decades (Section 4.4). Changing evaporation has been calculated from air temperature and precipitation data.

Table 4.5 shows calculated changes in the water-balance elements for the Caspian Sea with global warming. According to these estimates a considerable decrease (relative to the normal) in river water inflow to the Sea would occur by the end of the century, mainly due to decreased Volga River Runoff. This would be followed by a marked increase in inflow. Precipitation increases over the Sea would be particularly significant (up to 60% in the year 2020, from the current annual mean precipitation of 240 mm); evaporation would change insignificantly (up to 3%).

Table 4.5 Changes in components of the water balance of the Caspian Sea in response to global warming

Water balance component	Year 1989	2000	2020
Total inflow ($km^3\ yr^{-1}$)			
From map analysis	0	-20	+40
From model analysis	0	-30	+10
Precipitation (mm)	0	+100	+150
Evaporation (mm)	0	+15	+30

A simulation of water-balance components under varying climate conditions has been carried out by the same technique, taking into account, however, the data in Table 4.5 with interpolation for each year of the period under consideration. In this case, the shape of distribution curves, variability of water-balance components, coefficients of their autoregression and intercorrelation are accepted according to observational records. The results are presented in Figure 4.9. By the end of the century some lake-level lowering is expected to take place due to increasing human activities in the basin. After the year 2000, some stabilisation may occur followed by a significant rise in the Sea's level owing to predicted increases in inflow and precipitation over its surface (Shiklomanov, 1988; 1989a). These results, though preliminary, show the importance and necessity of taking into account anthropogenic climate change forecasts to estimate the fate of continental reservoirs and to plan future management.

5.2 The arid and semi-arid zones of North Africa, including the Sahel

North Africa and the Sahelian zone are both subject to frequent and disastrous droughts, progressive aridisation, and encroaching desertification. The Sahel, a vast though narrow, belt stretching from West Africa to the Horn of Africa, is the transition zone from the Saharan desert to the hot and semi-arid African savannahs. Analysis of annual precipitation data from stations in the Sahelian zone for the period 1968-88 indicate that this period was exceptionally dry. Although the current Sahelian drought appears to many scientists and policy makers to be a persistent and unprecedented phenomenon, this drought is far from unique. During the current century, the Sahelian region experienced several dry periods of varying duration, magnitude, and spatial extent (Grove, 1973; Sircoulon, 1976). During the last five centuries, historical accounts and palaeoclimatic evidence indicate that there have been rainfall fluctuations of extremely variable duration (from years to several decades) (Nicholson, 1978; 1989). Demarée and Nicolis (1990) viewed the Sahelian drought as a fluctuation-induced abrupt transition between a stable state of 'high' rainfall and a stable state of 'low' rainfall.

The major reason for Sahelian droughts is a decrease in annual precipitation. Ojo (1987) analysed precipitation data for 1901-85 using 60 stations in western Africa. He found that during 1970-79 average precipitation there was 62% of normal and, during 1981-84, about 50% of normal (Figure 4.10). The Sahelian zone is characterised by a strong sensitivity to hydrometeorological conditions, especially precipitation. This is confirmed by analysis of precipitation and runoff over the most dry and wet five year periods of time in the Senegal, Niger and Shari Rivers basins, as well as by Lake Chad levels and areas indicated in Sircoulon (1987). According to these data, with precipitation increasing by 20-30% the runoff rises by 30-50% in the river basins; with precipitation decreasing by 9-24% the runoff is reduced by 15-59%. In addition, between the early 1960s and 1985, the area of Lake Chad shrank by more than 11 times, ie from 23,500 km^2 to 2000 km^2.

The analysis of the series of total annual precipitation amounts from the stations situated in arid zones of Northern Africa for the period 1972-87 shows a trend toward decreasing total annual precipitation. The total annual precipitation amounts are much below normal (during the period in question). Likewise for Sahel, it is a succession of dry years that has created a critical situation in the region. This succession of dry years has led to decreasing water resources in region. An analysis of the number of rainy days during which a considerable amount of precipitation was observed showed a decrease toward days with small amounts of precipitation. From the decrease in the number of rainy days, the coefficient of runoff decreases too, which is manifest in a general decrease in runoff. A change in the distribution of precipitation toward a decrease in the number of rain days, as well as a significant shortening in the length of the rainy season, have been mentioned by many authors who have analysed Sudano-Sahelian precipitation data for the last 20 years (see, eg Demar6e and Chadilly, 1988 and Erpicum et al, 1989).

In view of its recurrent but aperiodic character, this tendency may represent a potential risk of drought possibly contributing to the process of desertification and extension of deserts. It seems obvious that the future water resources, ecology and economies of countries in the Sahelian and arid and semi-arid zones will depend upon changing precipitation in the region due to the growth of radiatively active trace gas concentrations in the atmosphere.

An optimistic forecast has been proposed by Soviet climatologists for Northern Africa on the basis of palaeoclimatic reconstructions (Anthropogenic climatic changes, 1987). According to these data, in the next several decades annual precipitation may increase considerably as may total moisture and river runoff. The estimates obtained are very approximate and need thorough checking and improvement, based on more detailed information and different methods. The quality of the data, however, should not deter attempts to solve the problem of considering climate variability in water resources management. In this regard two issues should be considered: water resources management problems and water quality problems.

The first issue is directly related to the sensitivity of hydrologjc systems to climate changes and, in particular, to droughts and floods. This necessitates taking into account risks while developing water resource projects. The second issue is related to water quality, ie the problem of pollution in relation to both human activities and natural processes. From the standpoint of anthropogenic climate change, there is no evidence to suggest that the drought problem for Northern Africa and the Sahelian zone will be reduced. Finally, taking into account the importance of climatic and hydrologic data for use in economic analyses of the African continent, there is a clear need to establish (i) systematic networks for meteorological data monitoring, and (ii) improved and expanded surface hydrologic data collection networks.

5.3 Water conditions in critical agricultural regions

5.3.1 The South Platte River

Next to the direct impact on water resources, perhaps the most critical social and economic concern associated with climatic change is the impact on agriculture. This is especially true in marginal farming regions of dryland farming or those that are heavily dependent upon irrigation for the maintenance of agricultural productivity. An example of such a region is the South Platte River basin in the west-central part of the US. The basin is primarily in the State of Colorado, but the river also drains parts of southwestern Nebraska and southeastern Wyoming (Figure 4.11). It is watershed number 1019 which drains into Water Resources Region 10, the Missouri River basin. The basin comprises 62,210 km^2 of mountains, plains foothills and alluvial fans. The western part is dominated by the rugged mountains of the Front Range, which is part of the Southern Rocky Mountains in Colorado. Of the 49,250 km^2 of the basin in Colorado, about 20% is above 2700 m in altitude, and more than half is above 1800 m. A few peaks rise above 4000 m.

Land use is diverse in the South Platte River basin. Most of the mountain area remains as near-natural National Forest land, with coniferous trees as the dominant vegetation. These forest lands are not extensively logged, and are now used mainly for recreation. Some of the lower slopes of the mountains are used for grazing. The transition area between the mountains and the plains includes most of the urban and suburban development. The plains are used principally for pasture and rangeland, dry cropland, and irrigated cropland.

By 1980, the basin had about 75 surface reservoirs with storage capacities of at least 6 million m^3, and about 300 other reservoirs with capacities of at least 0.6 million m^3. The total reservoir-storage capacity in the basin exceeds 2.5 billion m^3 (US Army Corps of Engineers, 1980). The reservoirs are operated primarily for irrigation, and public supplies, hydro-electric power generation, and flood control. However, recreation development has occurred on nearly all of the storage reservoirs in the basin (US Geological Survey, 1990). About 20 transbasin diversion structures have been used to import water into the South Platte River basin, including five tunnels and three pipelines US Army Corps of Engineers, 1977). The intensive development of water and lands in the South Platte basin has solved some problems while incurring others. There are still unmet demands for municipal and agricultural water supply. Groundwater overdrafting is occurring as a consequence. Over 200 communities have flooding problems and water quality has diminished, partly from irrigation return flows and partly from non-point source pollution.

The South Platte River basin is typical of the agriculturally based economy of the US Great Plains states, which includes a large livestock industry. Farmers in the Great Plains are particularly vulnerable to climate variability and the drought of the 1930s was so devastating, serving as the impetus for a large-scale social migration. The Great Plains has become a productive agricultural area in the US thanks to the large degree of water resources development. In its natural state, however, it is a marginal agricultural region and is very sensitive to climatic variability.This fact leads to considerable concern when current estimates of climate change are factored in. A comparison of the output of general circulation models, under doubled CO_2 conditions, show that both the GISS and GFDL models predict a net annual decrease in precipitation for the Great Plains region. The OSU models, on the other hand, shows a slight increase over present conditions, even during the critical summer period (Figure 4.12). The largest predicted summer season precipitation deficit is nearly 5 mm/day, according to the GFDL model, which is of the same order of deficit experienced during the devastating drought of the 1930s.The 2,301,000 people in the South Platte basin use 6894 litres per capita per day of fresh water for a total of 15,873 ML/day. Of this total, 4635 ML/day are withdrawn from groundwater sources and 11,237 ML/day from surface water sources. Irrigation is by far the largest user of fresh water (11,237 ML/day), of which 4271 ML/day if from groundwater sources and 6962 ML/day is from surface water resources. About 90% (9911 ML/day) of the water used for irrigation is lost by conveyance or consumption. Thermoelectric cooling uses account for 2247 ML/day and a consumptive loss of 53 ML/day. Publicly supplied water, largely for municipal uses, accounts for 2001 ML/day from surface water sources and 171 ML/day from groundwater sources.

Clearly, the doubled atmospheric CO_2 general circulation model simulations (except for those of the OSU model), if true, depict a potentially serious climate change scenario, particularly for the agricultural sector. Despite the large amount of irrigation, most of the farming in the South Platte River basin and the Great Plains is dryland. Only about 10% of the farmland is irrigated. The fact that 30-50% of all irrigation is from groundwater, which is already being rapidly depleted, does not bode well for any climate change scenario which greatly exacerbates current conditions.

In general, results of recent studies show a net reduction in crop (wheat and corn) yields, even with the compensating effects of CO_2 on plant photosynthesis (Smith and Tozan, 1988). Dryland farming would likely become increasingly risky and less economical. Moreover, the present water resources base (both surface and groundwater) could not compensate for the relatively large loss of marginal dryland acreage.

Navigation and hydroelectric power production on the mainstem reservoirs could be threatened as could surface water quality. Development of the basin's surface water potential is near capacity. Substantial changes in present water use technologies, particularly for irrigation, would have to be undertaken to meet the more stressful conditions postulated under the modelled climate change scenario. This encompasses increased water use efficiencies, conjunctive use of surface and ground waters, transfer of water rights and, lastly, major new imports of water from outside the basin.

5.3.2 The Murray-Darling Basin (Australia)

Another detailed look at the hydrologic and water resources impacts of a climatic change in a critical agricultural region has been completed for the Murray-Darling Basin in southeastern Australia (Stewart, 1989; Figure 4.13). In this basin, which has an area of 1.06 million km^2, about 10 million of the 12.4 million ML of water per annum available under present climatic conditions have already been developed and mean water usage already exceeds 8.6

million ML (Zillman, 1989). The region presently accounts for just under 60% of mean annual water use and includes 75% of the total irrigated area of the continent (1.7 million ha). The Murray-Darling Basin must be regarded as extremely vulnerable to the effects of climate variability or change and is of major socioeconomic importance to Australia.

The Australian analysis evaluated water resources impacts on the basis of output from five atmospheric general circulation models for both summer (DJF) and winter (JJA) seasons under equilibrium doubled CO_2 conditions. These included the GISS, GFDL, NCAR, OSU, and UKMO models. All of the models predict increases in surface air temperatures, ranging from 3°C to 7°C for the basin region. The models predict different changes in precipitation rates, including both increases and decreases, with a range 2.5 mm/day to 1.0 mm/day. The most widely used scenario of climate change in Australia is for a temperature rise of between 2°C and 4°C and precipitation increases up to 50% in summer (except in southern regions) and decreases of up to 10% in winter (Pittock, 1988).

Three distinct methods were used to estimate the estimate the potential impacts of these various model-generated climate scenarios; temporal analogs, spatial analogs, and hydrological models. Because the GCM models all predict increases in temperature of similar magnitude, and since global temperatures have undergone a modest increase over the past 100 years, temporal and spatial analogs operate on the assumption that the magnitude of the predicted global warming is correct. Although this assumption may or may not be valid, these procedures do provide one mechanism for understanding basin response to anomalous climatic conditions. Thus, periods of above average temperature in the historical record may provide indications of the potential impact of climatic change (temporal analogs). Areas with past climatic conditions similar to those expected in the future may also provide such indications (spatial analogs). Hydrological models can be used to determine the impacts of changes in precipitation and other factors defined by the scenarios or analogs.

Evaluation of the impacts of climatic change on a temporal basis can be studied in two ways. First, trends attributable to climatic change can be sought in recorded data and, if found, can be extrapolated into the future. Analysis of available temperature, precipitation, and runoff data from the Murray-Darling basin has not revealed any trend attributable to climatic change. This does not discount the possibility of climatic change but, rather, indicates that impacts are not yet discernible. The predictions of the general circulation models are for increasing temperatures across Australia of the order of 4°C to 5°C. If these changes are realised, the annual average temperatures in the southern part of the basin could rise to between 17°C or 18°C, while those in the northwestern region could increase to between 25°C and 26°C. Spatial analogs, that is using areas in Australia that currently have such temperature conditions to estimate future climatic patterns, would suggest that precipitation in both regions could decrease by 40% to 50%. Spatial analogs, however, can be misleading because not all characteristics are maintained in the analogous area. The differences can be in terms of vegetation types, topography, storm types and mechanisms, and moisture sources. Some of these characteristics may cause feedback mechanisms. It should be noted that the majority of the GCMs predict increases in precipitation, not decreases as suggested by the temporal and spatial analogs.

Close (1988) used computer models to examine how the River Murray system would have behaved if the current storages and current irrigation developments had existed for the last 94 years. By superimposing predictions of climatic changes assumed to be associated with the greenhouse effect, the impacts on water resources and system operation were estimated. Close concluded that:

(i) Tributary flows will increase over almost all of the Murray-Darling basin.

(ii) Flow increases will be more pronounced in the northern rivers of the basin than in those in the south.

(iii) Spring, autumn, and summer precipitation will increase while winter rainfall may decrease slightly.

(iv) Demand for irrigation water per hectare will decrease slightly.

(v) The water resources available for irrigation will increase, which will permit either the area of irrigation to be increased or the security of supply of the current irrigation areas to be improved.

(vi) Dilution flows will increase and hence salinity in the lower river will decrease.

It should be noted that these impacts are based on only one scenario, which does not agree with those provided by the majority of GCMs, or with the temporal and spatial analogs. The value of models is that they can be used to determine the impacts of a range of scenarios and to establish the most sensitive climatic parameters in a region, on which to then concentrate.

5.4 Water conditions in intensively urbanised areas - the Delaware River Basin (USA)

Estimating the water resources impacts of climatic change in dynamic and intensively urbanised areas has some unique problems. Perhaps the most significant of these is that such areas frequently undergo major population, commercial and industrial changes over time periods of several decades. The water resources effects of these changes are likely to be more significant than any that would be attributable to climatic change over the same time frame. Thus, estimates of changes in total population and its spatial distribution, as well as changes in industrial and land use conditions, are as essential to the determination of future water resources conditions as are estimates of climate change. Unfortunately, experience to date indicates that the estimation of future demographic, industrial, technological, and land use conditions, when available, is generally unreliable (Osborn, 1986).

In the US, a recent study investigated the sensitivity of hydrologic and water resource conditions in the Delaware River Basin, an intensively urbanised basin on the middle Atlantic coast, to potential changes in climate (Ayers et al., 1990). This work evaluated water resources impacts using estimates of climate change both with and without estimates of social and economic change.

The Delaware River Basin is an environmentally diverse region encompassing an area of approximately 33,000 km^2 and crossing five major physiographic provinces and three distinct ecosystem types. Runoff processes differ considerably over the basin; in addition, human activities influence the movement and storage of water in the basin, adding considerable complexity to the hydrologic response characteristics of the various physiographic provinces. Urbanisation in the lower portions of the basin has significantly altered the regional runoff response (Ayers and Leavesley, 1988).

With respect to climatic change, perhaps the most important issue is that the Delaware River provides water for an estimated 20 million people (Delaware River Basin Commission, 1986). Water availability is enhanced by complex systems of reservoirs for storage, and wells, pipes, tunnels, and canals for diversion and delivery. Moreover, the lower one-third of the river is tidal, and the freshwater part of the tidal river serves as a major source of groundwater recharge for aquifer systems supplying water to regions around the river and as an important water-supply source for the City of Philadelphia and many industries by direct diversion. It is critical, therefore, that the water in this stretch of the river remain potable, even during periods of prolonged low flow (droughts). This is the social and environmental context within which the Delaware Basin study was conducted.

Models of monthly streamflow (with and without reservoirs) and daily streamflow (without reservoirs) were developed to analyse the effects of climatic change on basin runoff. Analyses of the sensitivity of monthly streamflow to change in climate using a monthly water-balance model without reservoirs, and without changes in water use, indicate that warming could result in an increase in the proportion of winter precipitation that falls as rain in the northern part of the basin (McCabe and Ayers, 1989). The effect of such a change would be to reduce snow accumulation, increase winter runoff, and reduce spring and summer runoff. Basin-wide estimates of total annual runoff indicate that warming of 2°C-4°C, without corresponding precipitation increases, could produce a 9% to 25% decrease in total annual runoff as a result of increased evapotranspiration. The simulations suggest that an increase in precipitation of about 3% would be needed to counteract decreases in runoff that would result from each 1°C of warming. Annual runoff changes estimated from the water-balance model driven by climate change values generated using three GCMs ranged from -39% to +9%.

Similar sensitivity analyses using a stochastic monthly flow model with reservoirs indicate that the risk of drought is significantly greater in those climate change scenarios where precipitation does not increase sufficiently to offset the temperature increase. In one instance, water use was held constant at 1986 levels, that is, it was assumed that there would be no demographic, industrial, or technological changes occurring contemporaneously with climate change. The simulations indicated that the percentage of time that the basin would be under drought warning or emergency could increase. The probability of entering a drought condition in the Delaware River Basin currently is 9.5%, based on a 1000-year simulation (Table 4.6). Under assumed warmings of 2°C and 4°C, the probability of drought in the basin increases by 1.9 and 2.9 times respectively. When the two warming scenarios are accompanied by a 10% decrease in average precipitation, the probability of drought increases to 4.8 and 6.4 times the probability under current conditions respectively. A 10% increase in average precipitation in conjunction with a 2°C warming actually causes a decrease in the probability of drought. The simulated range in the amount of time the basin would experience drought, from a 60% decrease to a 540% increase, corresponds to the uncertainty associated with potential climatic change in the basin.

The simulation results presented in Table 4.6 indicate that virtually no change in the probability of drought will result from the projected growth in consumptive water use in the basin. Currently, however, a drought is defined only by the contents of the New York City reservoirs, and the magnitude of consumptive water use in the upper part of the basin is small relative to the diversions to New York City and to the increased evapotranspiration that could accompany a temperature increase.

Table 4.6 Simulated percentage of time in which the Delaware River Basin is in a drought warning or emergency condition*

Change in temperature	Change in precipitation -10%	None	+10%
For observed 1986 water use			
None		9.5	
+2°C	45.8	17.7	5.6
+4°C	61.1	27.2	10.3
For estimated 2040 water use			
None		9.6	
+2°C	46.0	17.8	5.7
+4°C	61.3	29.3	10.4

* For prescribed temperature and precipitation scenarios (Ayers et al., 1990)

A topographically based hydrologic model was developed and linked with a wet/dry climate model to assess the sensitivity of daily streamflow to climatic change in the Delaware River basin (Wolock et al., 1989). The sensitivity of streamflow in on-urban watersheds in the Delaware River basin to climatic change was evaluated using this daily flow model. The model stochastically generates time series of temperature and precipitation and uses estimates of parameters derived from watershed topography (Price et al., 1989) and soil hydraulic properties to generate a time series of streamflow.

A series of 60-year simulations, each representing a different possible future realisation of the same climatic change projection (a gradual warming of 3°C with current precipitation characteristics) was performed. Annual and monthly maximum daily streamflow and Kendall's tau statistics then were calculated for each of the 60-year streamflow time series to detect trends in streamflow.

These simulations illustrate two important characteristics about the sensitivity of basin watersheds to climatic change. First, seasonal differences in the expected effects of global warming on streamflow are observed. Maximum daily streamflows increase with time (more positive than negative trends) in mid winter months, decrease in spring and summer, and change little in fall and early winter. These seasonal differences in trend primarily reflect changes in snowfall accumulation and snowmelt. With warming, more winter precipitation falls as rain than as snow, and snowmelt occurs earlier. The warming effect is strongest in the northern part of the basin where snow accumulation currently is significant. Second, natural variability in precipitation masks the effects of increasing temperature. The percentage of simulations that do not show a significant increase or decrease is greater than 58% in any month and average 84%. Results of the simulations using the daily watershed model (without reservoirs) indicate that, overall, warming alone would cause a decrease in daily streamflow, specifically the maximum and average daily low and 7-day low flow. Most of this decrease would occur in the warmer months. Where snow accumulation currently is significant (in the northern part of the basin), however, the warming would result in an increase in the February average and maximum daily flow, regardless of precipitation changes. In general, watershed runoff was found to be more sensitive to changes in daily precipitation amounts than to changes in daily temperature or precipitation duration. Detectability of runoff changes was masked by the underlying variability in precipitation.

5.5 Regions of snowmelt-generated runoff: The Sacramento-San Joaquin River Basin (USA)

The Sacramento-San Joaquin Rivers comprise the drainage basin of the Central Valley of California, one of the most productive and diverse agricultural regions in the world (Figure 4.14). It encompasses several large metropolitan areas, and sustains many others. Over 40% of California's total surface water drains from the Central Valley Basin into the San Francisco Bay area, supplying water for irrigated agriculture, municipal and industrial uses and numerous other recreational and ecological purposes.

Elevations in the basin range from sea-level in the Sacramento-San Joaquin River Delta to mountain peaks of over 4,200 m in the Sierra Nevada range.

California's climate is characterised by wet winters and dry summers, with mean annual precipitation decreasing from 190 cm in the northern Sacramento River basin to 15 cm in the southern San Joaquin River basin. The key feature of the hydrologic characteristics of this basin is that a significant proportion of the basin's precipitation falls as snow in the high mountains. Consequently, storage of water in the snowpack controls the seasonal timing of runoff in the Central Valley rivers and has shaped the evolution of strategies for water management and flood protection (Smith and Tirpak, 1989).

California's rivers are highly regulated because its water resources are poorly distributed relative to its settlement patterns. Nearly 70% of the state's surface water supply originates north of Sacramento, while 70% of its population and 80% of the total demand for water lies to the south. About 85% of the Central Valley basin's total annual precipitation occurs between November and April, whereas peak water use occurs during the summer. About 826,000 ha are irrigated in the Sacramento River basin by groundwater and surface water sources. An additional 794,000 ha are irrigated in the San Joaquin River basin. Roughly 60% of the total population of California (26 million) is served by surface water sources, the remainder derived from groundwater.

Gleick (1989) reported that the drought of 1976-77 combined two of the driest years on record and resulted in a reconsideration of systemic water management procedures and their effects on the economic infrastructure of region. As an example of the severity of the drought, average annual precipitation in California is approximately 250 billion m^3. In the 1976 water year, precipitation decreased to 160 billion m^3, followed by even less precipitation in 1977, totalling 135 billion m^3, or 45% of average. Runoff in California's river dropped to 47% of normal in 1976 and to 22% in 1977.

Hydroelectricity is a major source of power in California, providing approximately 20% of the state's total electricity production. In 1976, total hydroelectric output dropped to just under 10%, while in 1977 it dropped to 7%. The reduction in relatively inexpensive hydroelectric energy production occurred as the need for groundwater pumping increased dramatically as a consequence of drastically reduced surface water deliveries. In 1977, 4.2 billion m^3 more water than normal were pumped from groundwater reservoirs (Gleick, 1988).

Droughts have a direct effect on salinity intrusion from San Francisco Bay into the Sacramento-San Joaquin Delta region. Upstream reservoirs changed their operating policies in the 1980s to prevent the worst effects of salinity intrusion during low flow years at the expense of increasing the vulnerability of the entire water management system. Flooding is a continuing major problem in the central basin and, as urbanisation increasingly spreads out onto the flat Central Valley, flood damages will increase proportionately.

Gleick also sees evidence of increased runoff variability in the long term record of the Sacramento River basin as expressed by the five-year moving average of the standard deviation of the Sacramento Basin unimpaired runoff record of 1906-86. This relatively recent increase in variability (since the 1970s) has resulted in a series of changes in standard planning and design assumptions about peak flood volumes, drought severity, recurrence intervals and reservoir operating rules. Thus, one of the likely future climatic states of global warming could be one in which there is a decrease in the mean runoff and an increase in variability, ie an increase in the frequency and magnitude of floods and droughts.

An assessment of the possible water resources impacts of a doubling of atmospheric CO_2 has been made using the output from three GCMs. It should be noted that conditions for the entire Central Valley drainage system are encompassed within one grid cell for each of the three GCMs. Again, there is considerable diversity among the three models, especially with regard to the seasonal prediction of precipitation changes. Nevertheless, based on a series of hydrologic impact studies conducted through the US Environmental Protection Agency and reported in Smith and Tirpak (1989), it was shown that total annual runoff in the Sacramento-San Joaquin River basin might be expected to remain near current levels or to increase somewhat under the scenarios simulated by each of the GCMs. However, major changes could probably occur in the seasonality of the runoff. In response to higher temperatures, less precipitation would be expected to fall as snow, and the snowpack that does accumulate could melt earlier in the year. Thus, there could be higher runoff in the winter months and considerably less in the traditional spring snowmelt-runoff season. Roos (1990) estimates that a 3°C temperature increase could shift about one-third of the present spring snowmelt into increased winter runoff. Also, the possibility exists for runoff variability to increase substantially during the winter season.

Change in the timing of runoff could have profound influences both on the aquatic and terrestrial ecology and on water resources management, despite the fact that total annual runoff could be slightly higher.

First, more liquid precipitation in the winters months could lead to reduced runoff in the late spring and summer, thereby reducing the carry-over soil moisture needed by the vegetation. Also, such a reduction in stream-flow in the late summer could lead to a degradation in the health of aquatic species.

An analysis of 1990 water use demands, in conjunction with instream flow constraints and delta outflow requirements and current reservoir operating policies, indicate a potential decrease in mean annual deliveries from 7% (OSU model) to 14% (GFDL model) to 15% (GISS model). This would occur because under current operating rules combined with earlier (ie winter) snowmelt, the reservoir would not have the capacity to store the early runoff for summer season irrigation withdrawals while simultaneously retaining springtime flood control capabilities.

Future demands for surface water from the Sacramento-San Joaquin system are expected to increase 30% by the year 2010. 'This demand could not be reliably supplied under the current climate and resource system, and the shortage might be exacerbated under either of the three GCM derived scenarios' (Smith and Tirpak, 1989). Furthermore, the potential magnitude of changes in the seasonality of runoff are such that operational changes alone would probably not significantly improve the systems performance.

Climate change impacts on agriculture are complicated by the fact that so much of it is dependent on irrigation, which accounts for 80% of California's water use. If there are substantial and persistent shortages as a result of the inability of current water management operating procedures to adapt to the change in seasonality, these deficits would clearly affect agricultural yields. However, two of the GCMs, the GISS and GFDL models, were used to predict changes in the yields of several different crops (sugar beets, corn, cotton, and tomatoes) under a doubling of CO_2 and the resultant potential changes in mean annual and seasonal temperature, precipitation and soil moisture. Under those direct conditions of climatic change, all the crops were simulated to suffer decreases in yield. When growth enhancing effects of a doubled $C0_2$ atmosphere were taken into account along with the primary climatic effects, all the crops (except corn) showed substantial increases in yield.

6 Conclusions

Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions and those humid areas where demand or pollution has led to water scarcity. Little is known about regional details of greenhouse-gas-induced hydrometeorological change. It appears that many areas may have increased precipitation, soil moisture and water storage, thus altering patterns of agriculture, ecosystems and other water uses. In other areas, however, water availability may decrease, an important consideration for existing marginal situations such as the Sahelian zone in Africa. This has significant implications for agriculture, water storage and distribution, and for hydroelectric power generation. In some comparatively small areas, assuming a 1°C-2°C temperature increase coupled with a 10%-20% reduction in precipitation, a 40%-70% decrease in annual or seasonal runoff could occur. Regions such as Southeast Asia, that are dependent on unregulated river systems, are particularly vulnerable to hydrometeorological change. On the other hand, regions such as the western USSR and western US that have large regulated water resource systems are less sensitive to the range of hydrometeorological changes in the assumed greenhouse scenario.

If meaningful estimates of water resources conditions, appropriate for planning and policy formulation, are to be produced, then studies must include estimates on the frequency, intensity and duration of potential future hydrologic events. This is especially critical for evaluating effects on agriculture, the design of water resource management systems, and for producing reasonably accurate water supply estimates.

In many instances, it can be expected that changes in hydrologic extremes in response to global warming will be more significant than changes in hydrologic mean conditions. Thus, attention must be focused on changes in the frequency and magnitude of floods and droughts in evaluating the societal ramifications of water resource changes.

Initial water resource planning and policy-making will continue to be implemented even in the face of uncertainty about global change. Clarification and specification of the useful information content of the various methods for estimating future change must be made available to the management community.

The most essential need is for more reliable and detailed (both in space and time) estimates of future climatic conditions. These estimates must be regionally specific and provide information on both the frequency and magnitude of events.

Increased understanding of relations between climatic variability and hydrologic response must be developed. Such work should include the developmenl of methods for translating climate model information into a form that provides meaningful data to watershed and water resource system models.

Areas particularly vulnerable to even small changes in climate must be identified worldwide. Vulnerabilities must be ascertained, considering both natural and anthropogenic conditions and potential changes.

Intensive assessments of water resource sensitivities are necessary in developing countries, especially those located in environmentally sensitive arid and semi-arid regions, where the potential for conflicts associated with low water resource system development and rapidly increasing water demands is high.

Studies are needed that produce improved procedures for operating water management systems in consideration of climate uncertainty. A related aspect of this work is the development of design criteria for engineered structures that specifically incorporate estimates of climatic variability and change.

Very little is currently known about the effects of climate change on water quality. Although water quality concerns are becoming increasingly important, the separation of human-induced versus climate-induced changes in water quality is a very difficult problem. Specifically, there is an immediate need to identify those aspects of this problem that hold the most promise for yielding credible evaluations of climatic effects on water quality.

Figure 4.1. Dependence of consumptive water losses, over large continental areas, on the aridity index. 1 - Africa, 2 - Europe and Australia, 3 - North and South America, and Asia

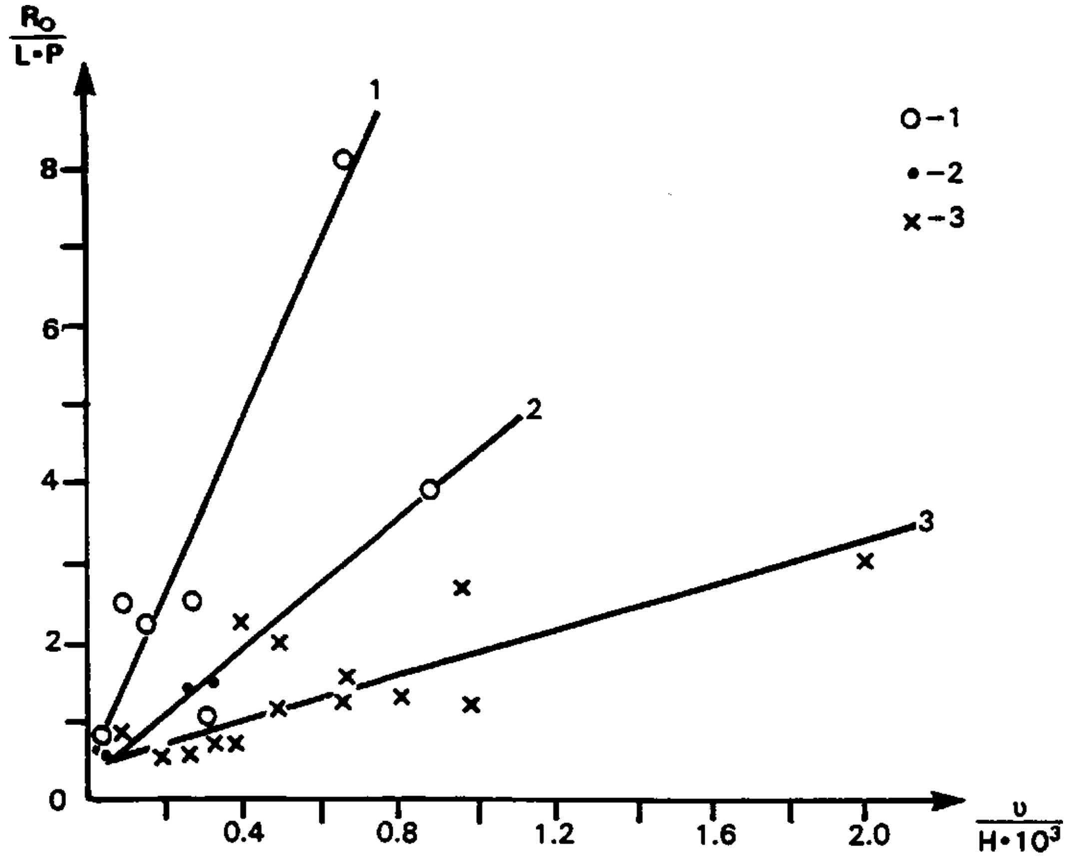


Figure **4.2.** Mean annual water supply (in billions of gallons per day) under current and hypothetical conditions for the major water resource regions of the US

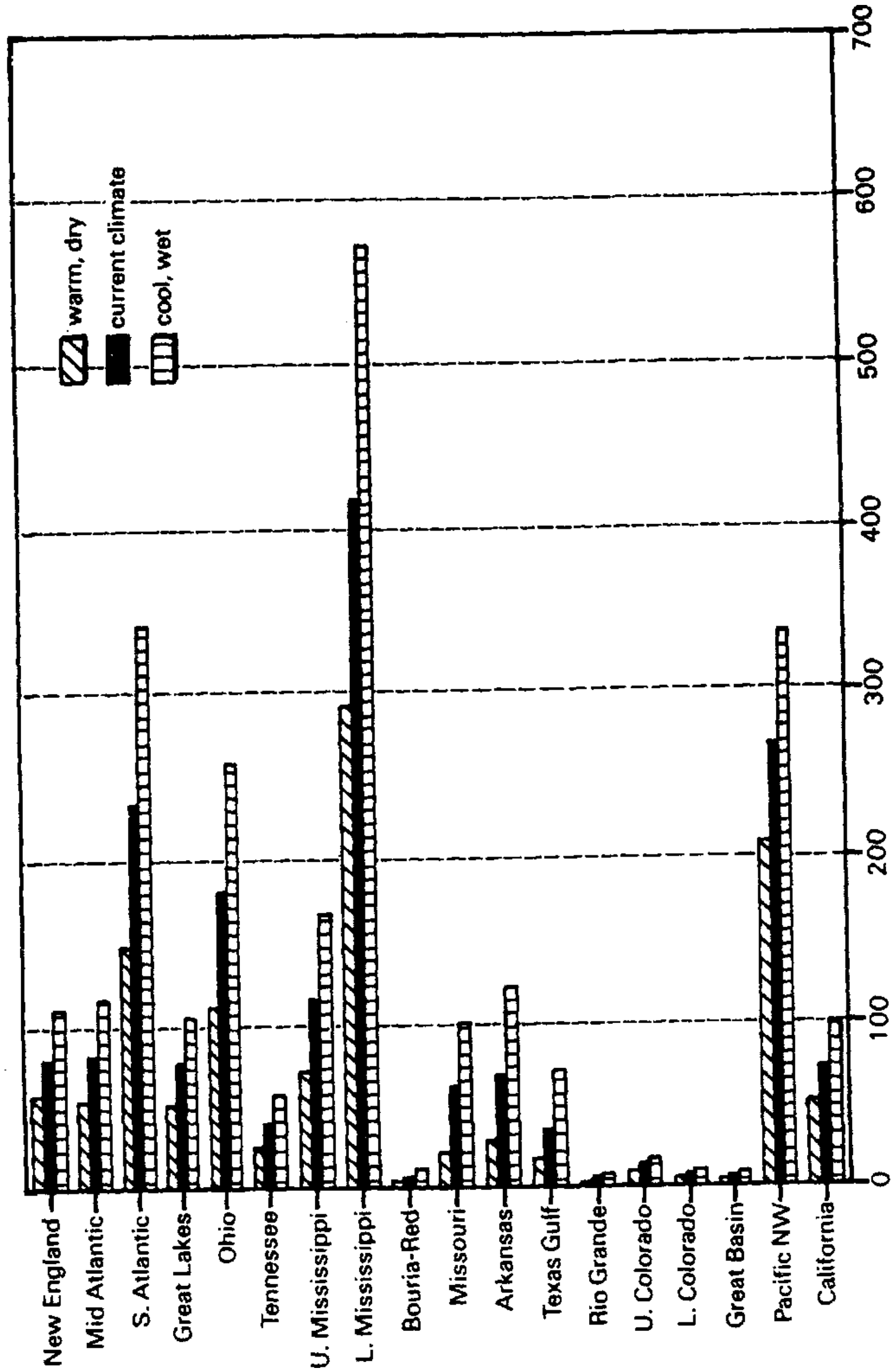
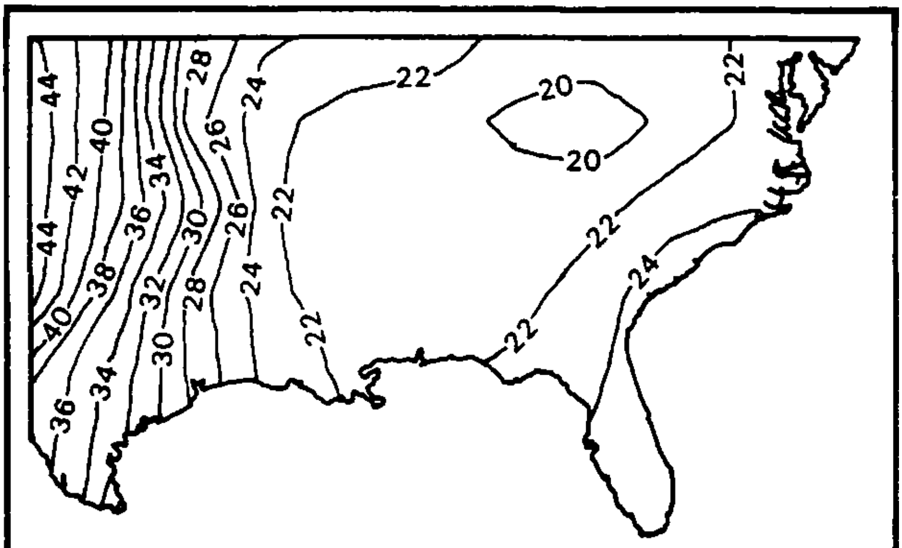
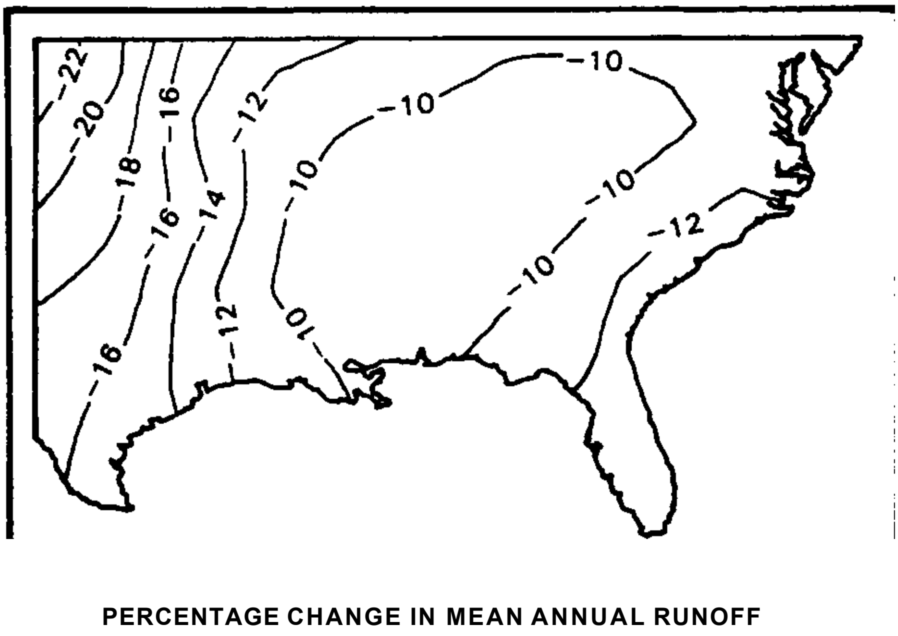


Figure 4.3. Percentage change in mean annual runoff by varying precipitation (upper) and potential évapotranspiration (lower) (Schaake, 1990)



PERCENTAGE CHANGE IN MEAN ANNUAL RUNOFF
PRECIPITATION +10%
POTENTIAL EVAPOTRANSPIRATION — NO CHANGE



PERCENTAGE CHANGE IN MEAN ANNUAL RUNOFF
PRECIPITATION — NO CHANGE
POTENTIAL EVAPOTRANSPIRATION +10%

Figure 4.4. Change in annual runoff (in centimetres) for the USSR as estimated for a warming of 1°

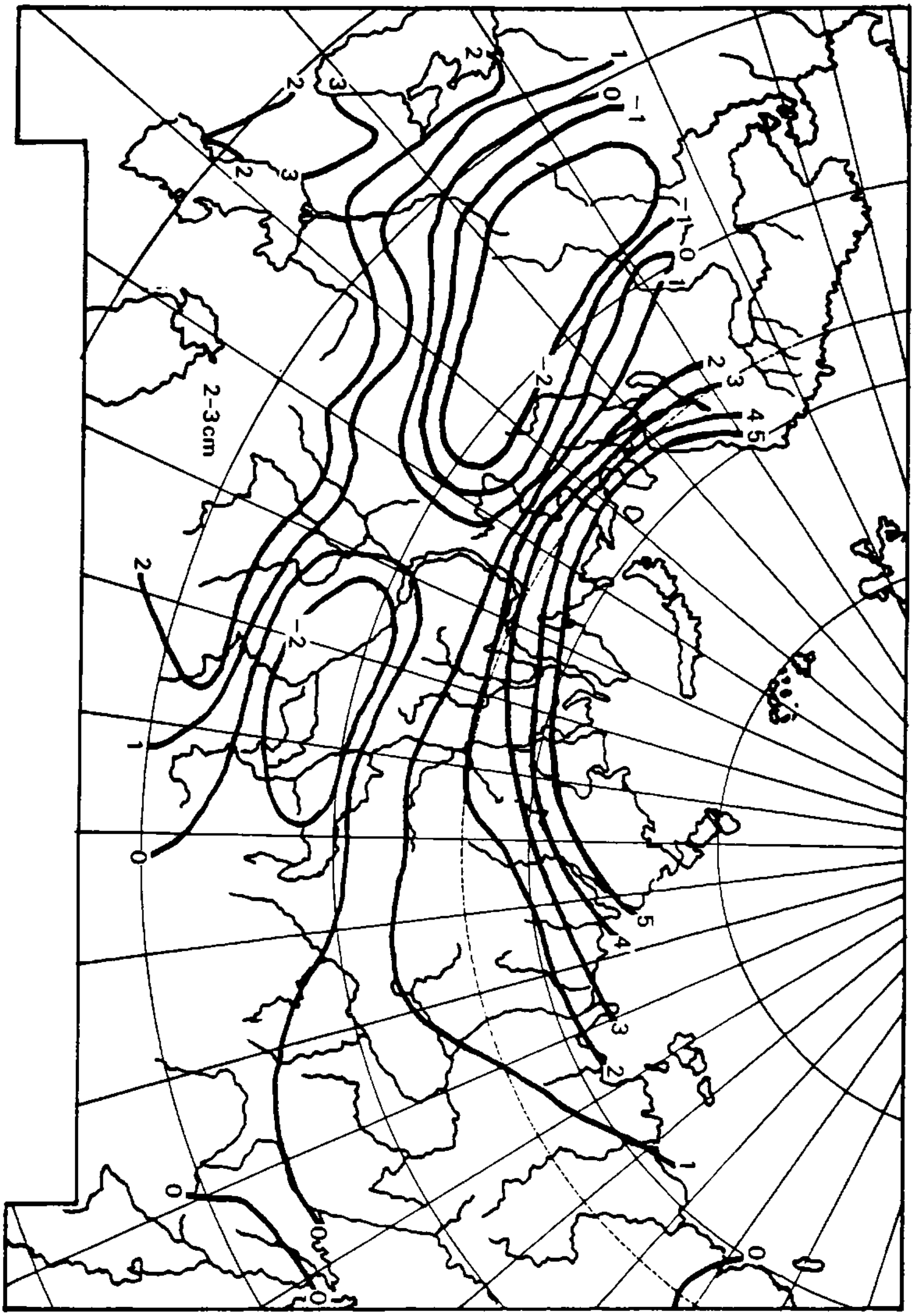


Figure 4.5. Estimated percentage change in annual runoff under climate change scenario SI (2030-2050) in New Zealand (Griffiths, 1988)

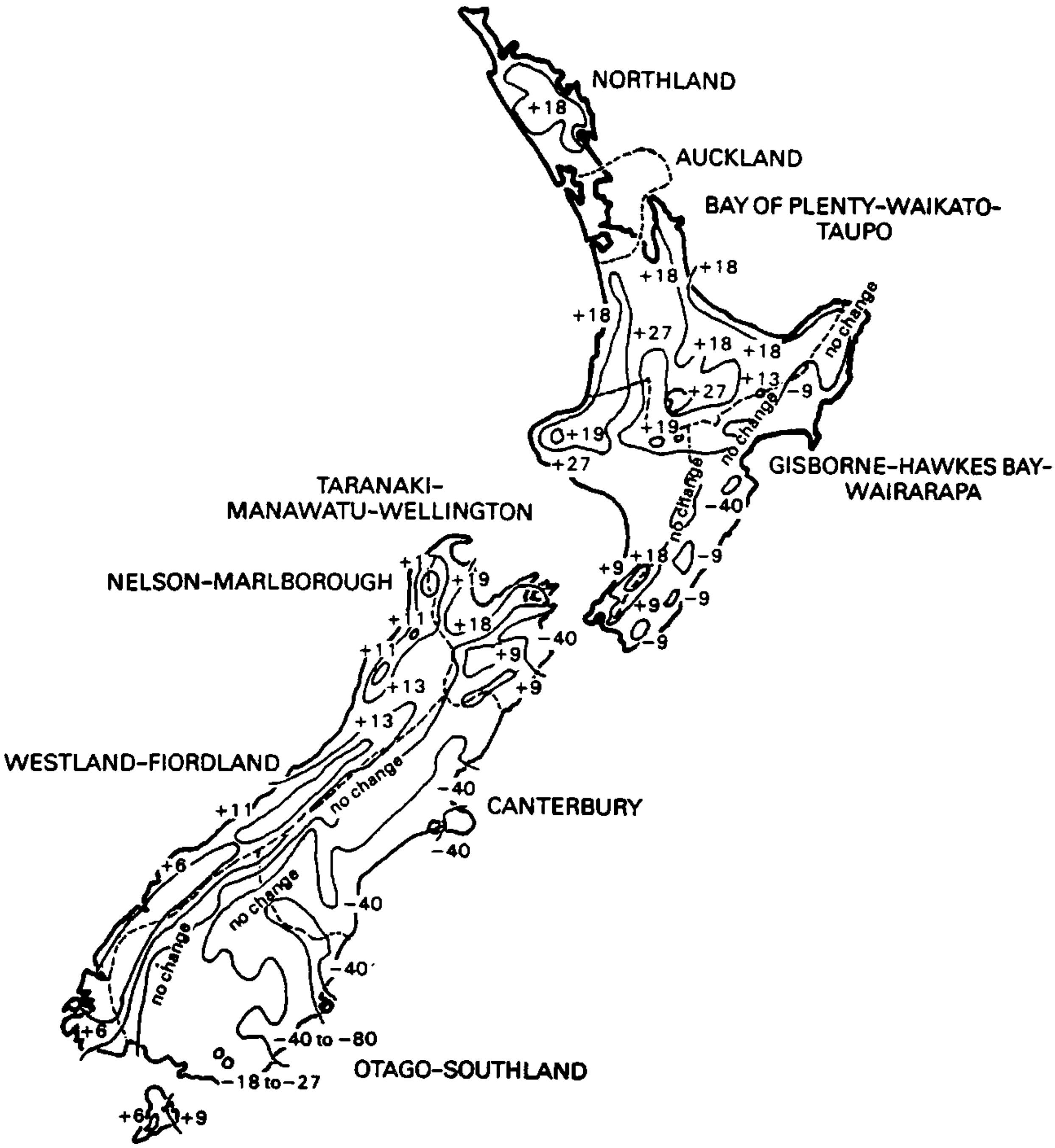


Figure 4.6. The Great Lakes drainage area (Smith and Tirpak, 1989)

Figure 4.7. GCM-estimated average seasonal and annual changes in temperature (upper) and precipitation (lower) for the grid cells encompassing the Great Lakes (2 x CO_2 minus 1 x CO_2) (Smith and Tirpak, 1989)

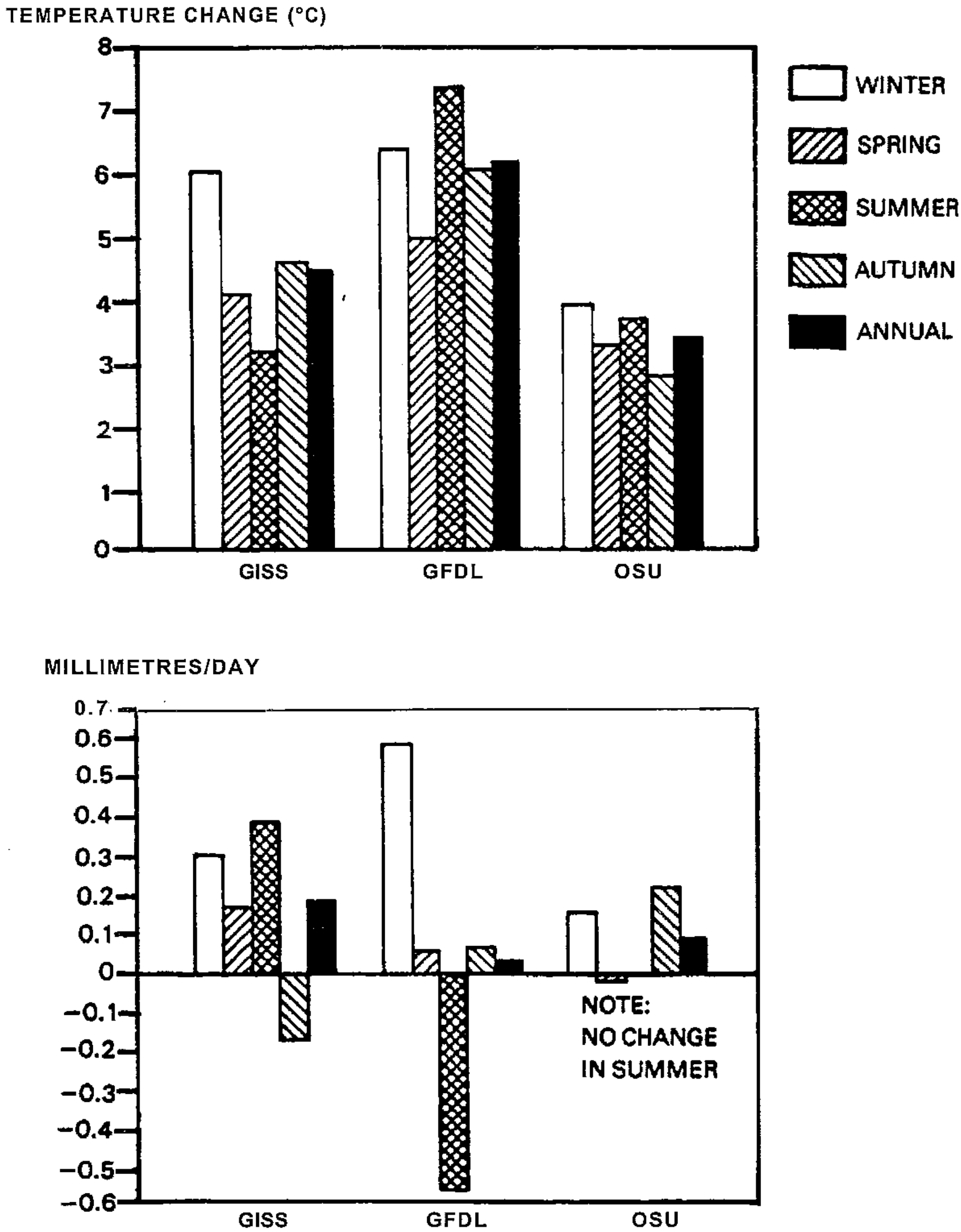


Figure 4.8. Comparison of actual levels of Lake Erie for the period 1900-80 with estimated levels for the same period generated by superimposing onto the actual conditions a warmer climate and a warmer climate with future levels of consumptive use (Sanderson, 1989)

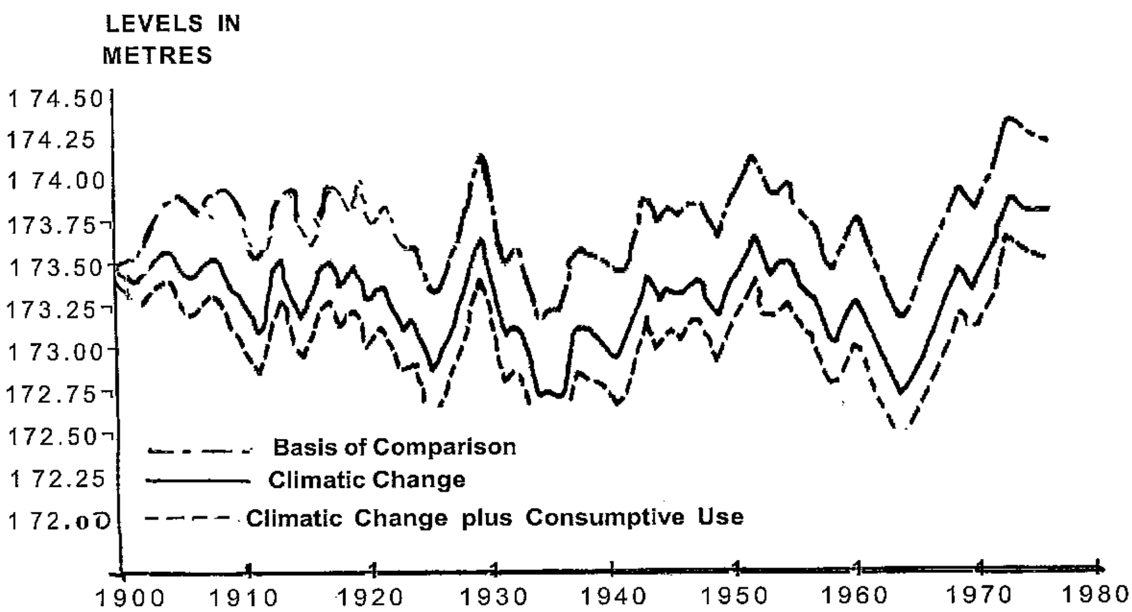


Figure 4.9. Estimated levels of the Caspian Sea, 1989-2020 under varying climate change scenarios: 1 - stationary climate with man's impact, 2 - model-based anthropogenic change in climate including man's impact, 3 - map-based anthropogenic change in climate including man's impact, 46 - observed lake level variations before 1988

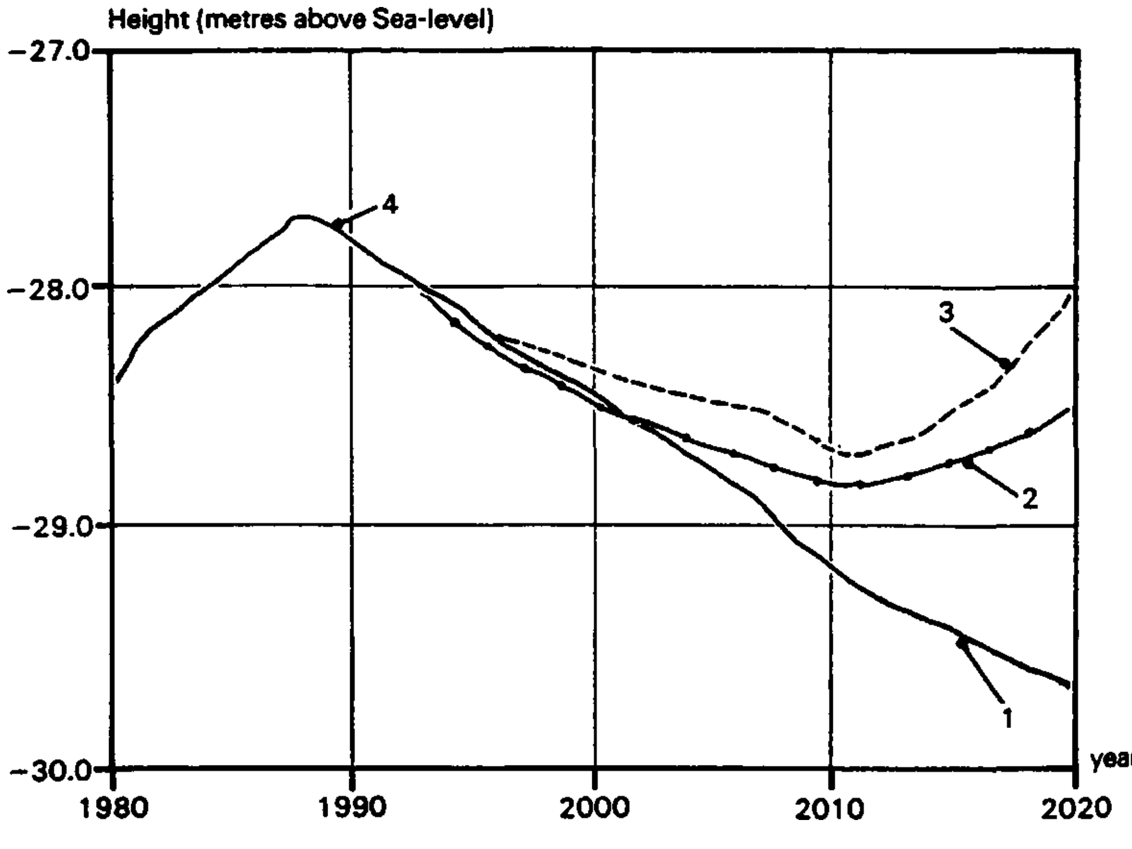


Figure 4.10. Plot of normalised annual average rainfall (solid line) and 3-year moving average (dashed line) for the town of Saint Louis, Senegal (upper, 1932-1982) and Oran es Senia, Algeria (lower, 1927-1987)

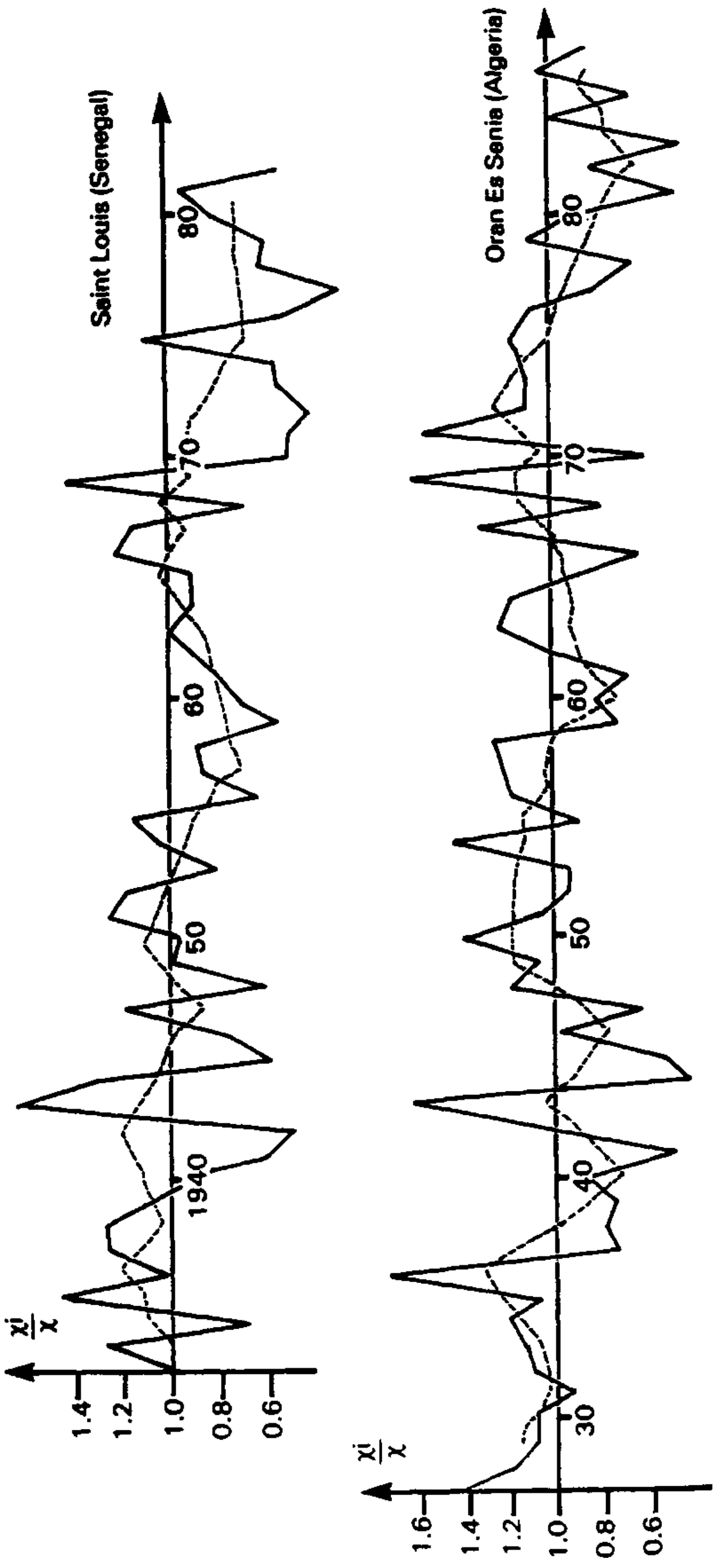


Figure 4.11. Drainage area of the South Platte River basin (US Army Corps of Engineers, 1977)

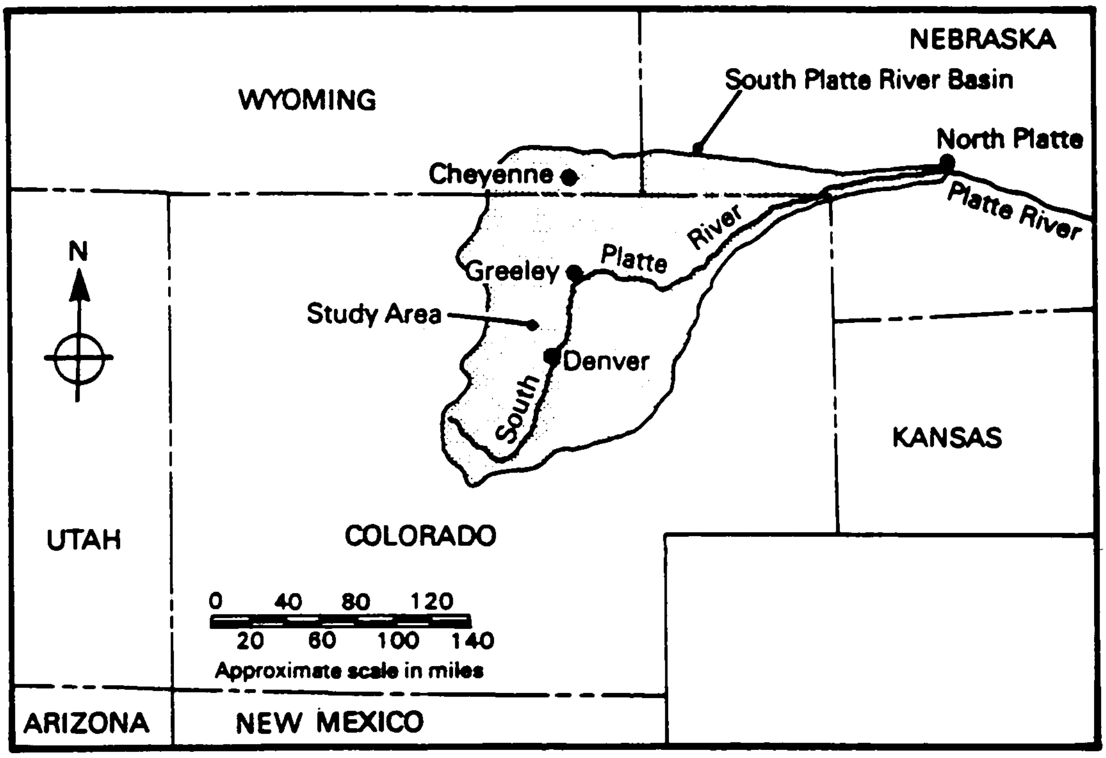


Figure 4.12. GCM-estimated average seasonal and annual changes **in** temperature (upper) and precipitation (lower) for the grid cells encompassing the Great Plains (2 x CO_2 minus **1** x CO_2) (Smith and Tirpak, 1989)

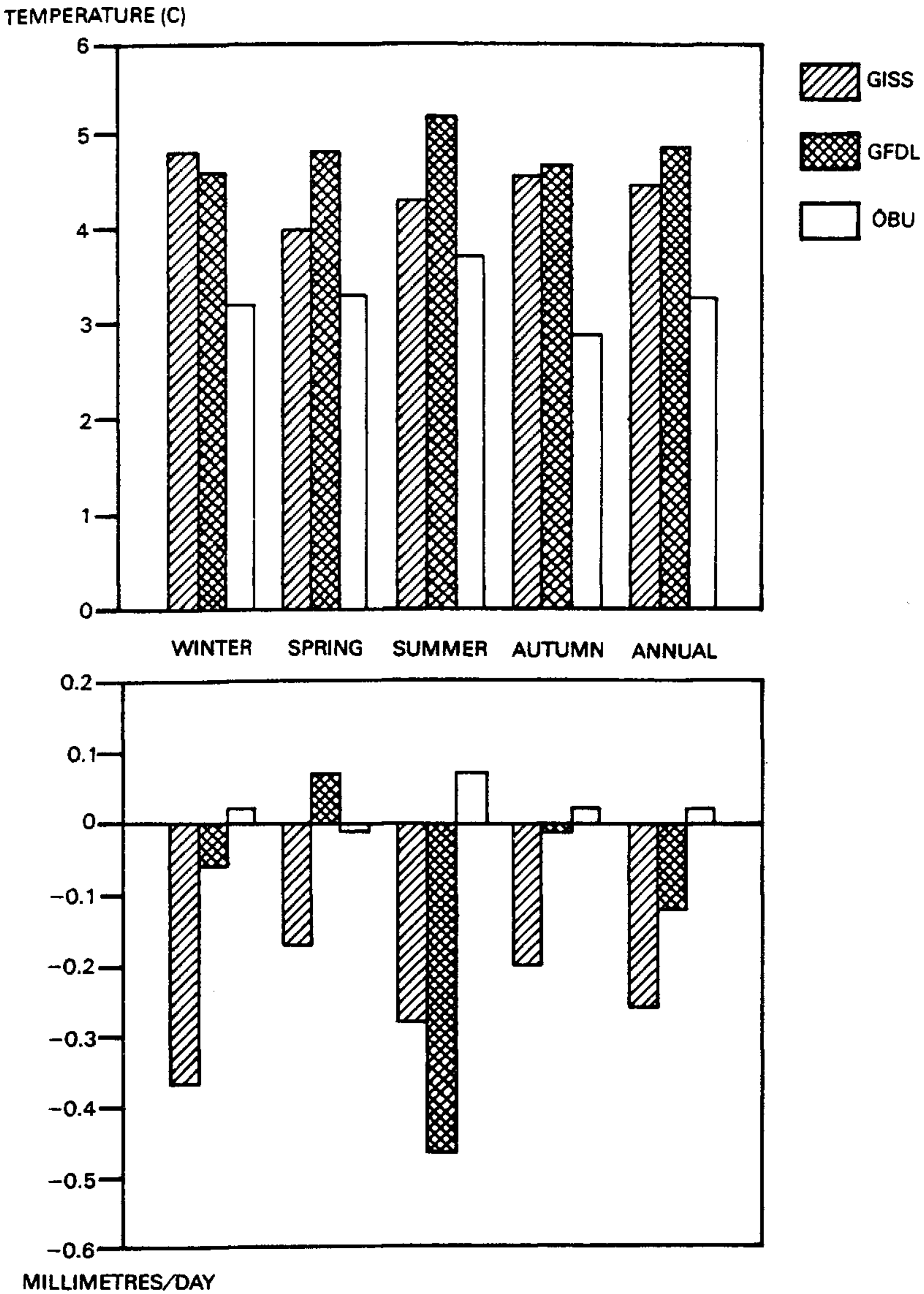


Figure 4.13. The drainage area of the Murray-Darling basin in southeastern Australia (Stewart, 1989)

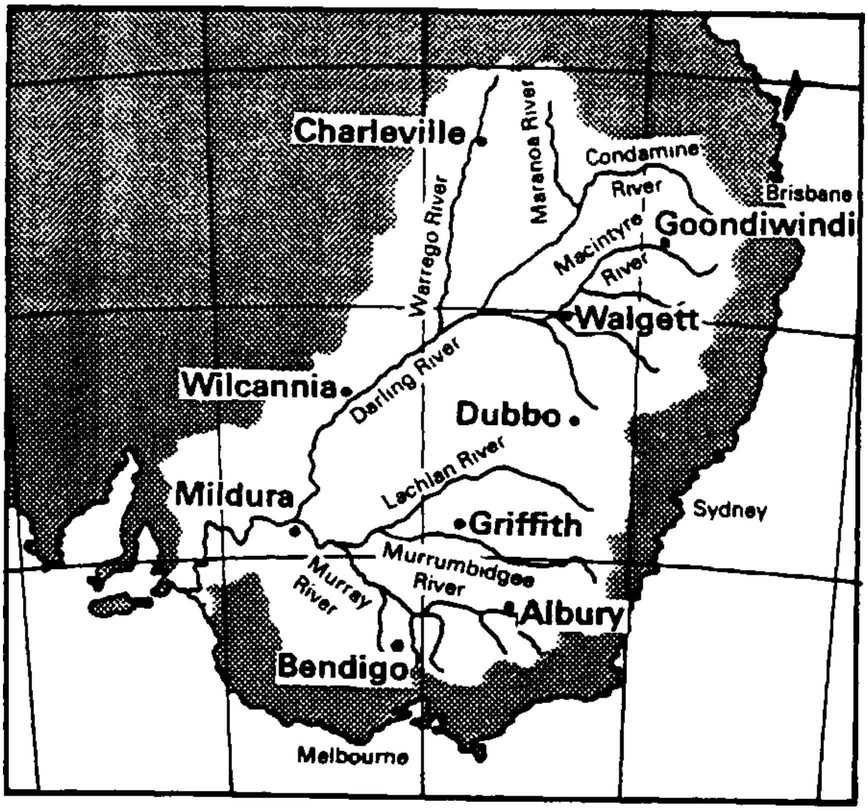
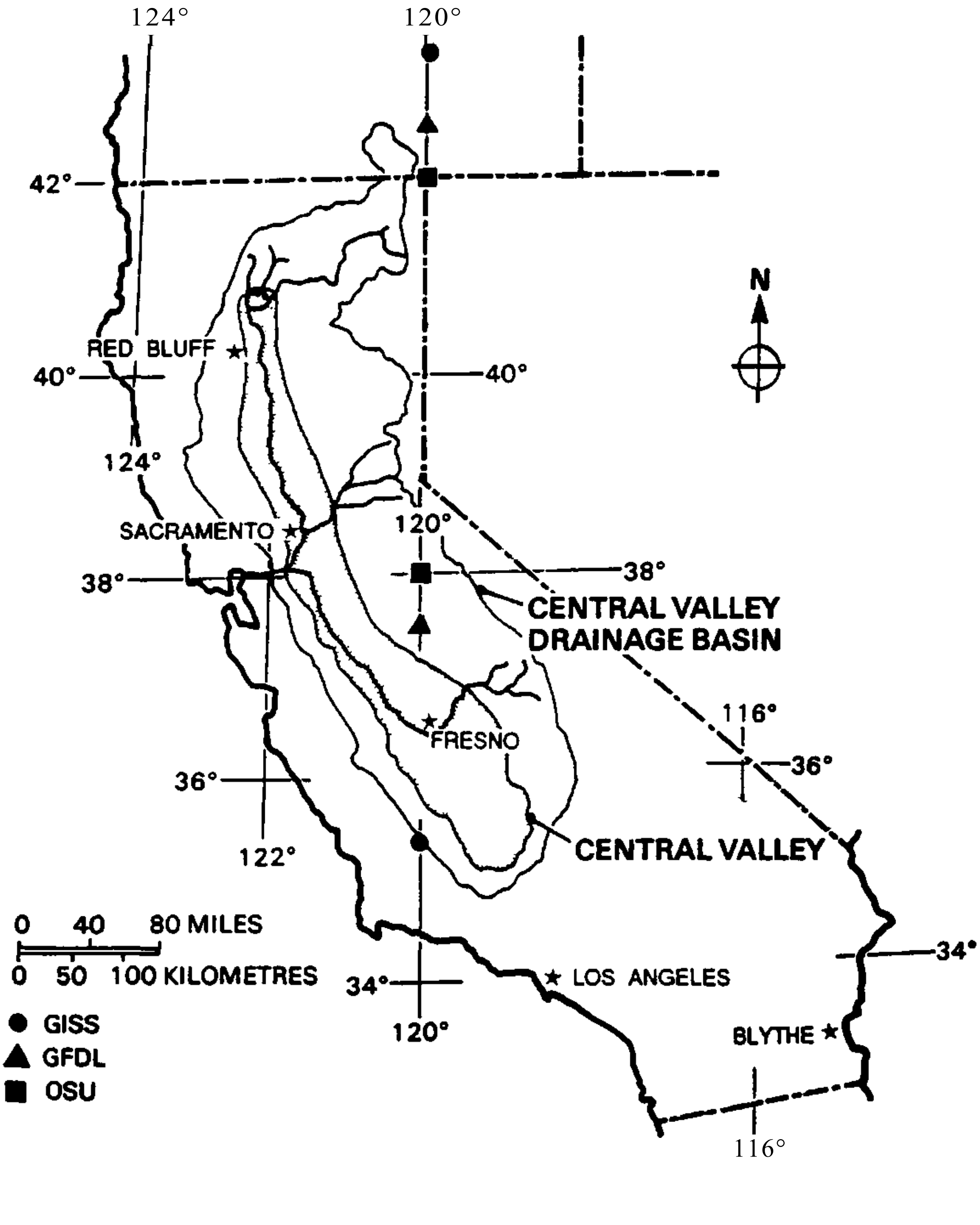


Figure 4.14. The Central Valley (shaded) and Central Valley Basin of California. Symbols refer to locations of the GISS, GFDL and OSU GCM gridpoints (Smith and Tirpak, 1989)



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Chapter 5

Human settlement; the energy, transport and industrial sectors; human health; air quality; and changes in ultraviolet-B radiation

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1 Overview

1.1 Introduction

This chapter covers a wide range of potential impacts of climate change. It addresses the implications of global warming, sea-level rise, changed precipitation and evaporation and stratospheric ozone depletion for human settlement, which includes housing and infrastructure, and for the energy, transport and industrial sectors. It also covers the likely impacts of global warming and stratospheric ozone depletion on human health and air quality, and the potential overall impact on human health and natural systems of increased levels of ultraviolet-B (UV-B) radiation reaching the earth's surface as a result of depletion of the stratospheric ozone layer.

Evaluating scientific predictions of global climate change is the responsibility of Working Group I. At present there are substantial scientific uncertainties about the nature and magnitude of climatic changes that might result from an effective doubling of CO_2 concentrations in the atmosphere. However, it is necessary to make some assumptions about changes in climate in order to assess potential impacts which are due to these changes. The general types of changes that serve as a basis for the impacts assessments are described below. They are not intended to be definitive. The assessments in each section of this report summarise studies in the literature that are based on varying assumptions about climate change; those assumptions are generally described for each study cited. Many impact assessments are based on projections of a particular General Circulation Model (GCM) for long-term equilibrium conditions due to an equivalent CO_2 doubling in radiative forcing, while others assume a particular change in temperature, precipitation, or other variables. Owing to the large heat capacity of the oceans, full realisation of equilibrium temperature increase associated with a radiative forcing is expected to be delayed a number of years.

A consensus exists among the world's leading scientists that a continuation of the current rate of increase in concentrations of greenhouse gases (GHG) in the atmosphere will cause a significant increase in global average annual temperatures. An increase in GHG concentrations equivalent in infrared absorbing effect to a doubling of pre-industrial levels of CO_2 is projected to occur between 2025 and 2050. This increase in concentrations of GHG could be expected at equilibrium, according to projections of Working Group I, to produce a rise in average annual global temperature of 2°-4°C. Although most climate impact scenarios have used effective CO_2 doubling, should current emissions growth continue GHG concentrations would be expected to rise past an effective CO_2 doubling.

1.2 Direct impacts of global climate change on human activity

Model simulation and palaeoclimatic evidence suggest that when climate warms, it warms more in higher latitudes than in lower latitudes and more in winter than in summer (Golitsyn, 1989; Schneider, 1989). A warmer atmosphere contains more water vapour and increases the intensity of the whole hydrological cycle, but precipitation patterns are likely to change homogenously in time and space (Golitsyn, 1989). Some scientists believe that in a warmer climate the earth can be expected to experience more variable weather than now, with a likelihood of more floods and drought, more intense hurricanes or typhoons, and more heatwaves (Golitsyn, 1989; Hansen et al., 1989).

The expected rise in global temperatures will affect human health, comfort, life styles, food production, economic activity, and residential and migration patterns. As global temperature rises, atmospheric circulation patterns are likely to change with alterations in the frequency and seasonality of precipitation and an overall increase in the rate of evaporation and precipitation. Coupled with the associated general rise in temperature, such changes in the water cycle will affect water availability, agricultural activity, flood protection practices, infrastructure planning and natural habitats. If the intensity of the hydrologic cycle increases, some scientists believe that humanity and natural systems may experience much more severe weather-related events such as droughts, floods and extremely severe tropical cyclones. One estimate is that an effective CO_2 doubling may increase the intensity of tropical cyclones or hurricanes as much as 40% (Emanuel, 1987). Along with this potential increase in the intensity of such storms, humanity can expect an expansion of the area vulnerable to tropical cyclones, with the areas of potential damage expanding northward in the Northern Hemisphere and southward in the Southern Hemisphere, perhaps exposing such populated areas as the eastern coasts of Australia (Henderson-Sellers and Blong, 1989). These projections of greater problems from tropical cyclones are based largely on calculations of effects of increased surface temperature. Although the area of sea having temperatures over this critical value will increase as the globe warms, the critical temperature itself may increase in a warmer world (Working Group I Report). Further studies may provide a much more definitive picture of likely impacts of global warming on tropical cyclone activity.

Together with the anticipated disruption in atmospheric circulation and storm patterns, humanity is expected to face a significant rise in global mean sea-level. Global warming will cause a thermal expansion of the upper layers of the ocean and this expansion, together with the expected melting and movement into the ocean of some land-based glaciers, is expected to accelerate the current sea-level rise trend. A rise of 9-29 cm is expected over the next 40 years, or 28-98 cm by 2090 (Working Group I Report - Summary). A rise of only 25 cm or more in relative sea-level would displace many residents of the delta regions of the Nile, the Ganges and the Yangtze from their homes and livelihoods and could render uninhabitable island nations such as the Maldives in the Indian Ocean, and Kiribati, Tuvalu and the Marshall Islands in the Pacific (Tickell, 1989). This projected sea-level rise will cause widespread coastal erosion, especially on gradually sloping coasts such as those in the Atlantic or Gulf Coasts of the US (Titus, 1988), or the West Coast of Africa (Murday, 1989).

One scientist has projected that a rise of 1 m in sea-level could seriously affect nearly a hundred million people along the coasts of China, particularly in the Pearl River deltaic plain containing the city of Guangxhou, the eastern half of the Yangtze River plain, in which Shanghai is situated, the eastern half of the North China coastal plain containing Tainjin, and the southern half of the Lower Liao River plain where the city of Yingkou is located (Han, 1989). Besides sea-level rise, perhaps attributable to greenhouse effect-induced global warming, tectonic factors and groundwater withdrawal have contributed to rapid rises in recent years in the sea-level along many parts of China's coasts. Although sea-level along the Chinese coast has generally risen 11.5 cm in the past 100 years, relative sea-level rise has been much faster in some low-lying coastal plains. Sea-level rose 0.75 m from 1954-1978 in the Pearl River deltaic plain and 1.3 m in the North China coastal plain around Tianjin; in recent years land settlement caused merely by groundwater withdrawal has exceeded 2 m in the downtown areas of Tianjin and Shanghai (Han, 1989).

In the absence of concerted human efforts to build coastal defences, a sea-level rise of 1 m could inundate the port area of 1900 km^2 and cause damage to nine million Japanese (Ministry of Transport of Japan, 1989). With industry in sub-Saharan Africa concentrated heavily in seaports, many of which are capitals (Tebicke, personal communication, 1989), even a modest sea-level rise could pose a major threat to the economy and political infrastructure of Africa. Chapter 6 discusses these potential impacts of sea-level rise in more detail.

1.3 Observed changes in global, regional and local climate

According to a study released early in 1989, 1988 was the warmest year of the past century in average global temperature (British Meteorological Office and University of East Anglia, 1989). The same researchers reported that 1989 was the fifth warmest year in the 134 years for which they have compiled global temperature records and that six of the ten warmest years on record were in the 1980s (Kerr, 1990).

Although climatologists disagree on whether the observed increase over the past century of about 0.6 °C in average annual global surface temperature is a clear 'signal' of greenhouse warming, or still within the natural variability of climate, there seems little dispute among climatologists that humanity has already significantly reshaped the earth's climate through such factors as the urban heat-island effect, intensification of desertification through land degradation, deforestation and stratospheric ozone depletion. These factors, some of which have arisen quite independently of the build-up in global concentrations of GHG, are likely to produce significant effects on humanity, often magnifying the disruption caused by a rapid greenhouse-induced global warming.

1.3.1 Potential intensification of the urban heat-island effect

Removal of vegetation, construction of buildings, roads, pavement and other human transformations of the natural environment, together with direct heat generation from human activity, are known to cause the temperatures of urban areas to rise above those of surrounding rural areas. In the US this urban heat-island effect was estimated at an average of just over 1.1°C for a sample of 30 US cities and about 2.9°C for New York City (Viterito, 1989). In Moscow, USSR, the heat-island effect is projected to add about 3°-3.5°C to average annual temperatures (Izrael, 1989).

The urban heat-island effect in Shanghai, China, is quite pronounced, with a potential intensity as high as 6.5°C on a calm, clear December night in 1979, but no heat-island effect observed on days with strong wind and heavy rain (Zhou, 1989). The urban heat-island effect has been reduced significantly in one city by large-scale tree planting. In Nanking, China, the planting since 1949 of 34 million trees has been credited with a significant cooling of the cities' average temperature (De La Croix, 1990).

Although the heat-island effect has tended to enter into global climate discussions largely in the context of whether some of the observed global temperature rise may be ascribed to the placement of some thermometers in urban areas, the heat-island effect has considerable independent significance for humanity. The rapid urbanisation of many developing countries is transforming the landscape of many cities. The continuing explosive growth of such cities as Cairo (Egypt), Sao Paulo (Brazil), Mexico City (Mexico), Lagos (Nigeria), Delhi (India) and many other urban megalopolises is likely to effectuate a profound alteration in the local climate. It is quite possible that a considerable temperature amplification in many such areas, attributable to the heat-island effect alone, might be added to an already sizeable projected temperature increase from greenhouse effect-induced global warming. Heat-stress impacts on health, human discomfort and aggravation of urban air-pollution problems, such as smog, are all possible consequences of an additive heat-island and greenhouse warming.

1.3.2 The growth of desertification following land degradation

Human actions such as overgrazing of agricultural lands, removal of tree cover and intensive agricultural practices have furthered soil erosion and have accelerated desertification which in the past was largely caused by natural climatic processes. Whether or not the current desertification is significantly linked to a greenhouse-induced warming trend, it is causing enormous dislocations and great human suffering in Africa. Thousands of nomads in Mauritania have been driven into urban areas and refugee camps, creating great social turmoil (Dadda, 1989). The dimensions of this problem were recently summarised by Lt Col Christine Debrah (Ret'd), Executive Chairman of the Environmental Protection Council of Ghana:

> As we are meeting here today, millions of Africans are suffering from hunger and malnutrition. Vast numbers of people are moving within and across national boundaries in search of food, thereby creating environmental refugees. There is, of course, no accurate measure of the extent of the crisis. But the orders of magnitude are indicative: 150 million people threatened by starvation or malnutrition and an estimated 4 million refugees and returnees and an untold number of displaced persons.
>
> Thus, in Africa, dry weather conditions have been experienced, leading to brushfires and further degradation of the land. (Debrah, 1989).

Yet some climate models project that this trend in much of Africa is likely to be exacerbated as the world warms, with increased drought in such places as northwestern Africa (Druyan, 1989, Hansen et al., 1989).

1.3.3 Regional climatic implications of deforestation

Wide-scale deforestation, besides its contribution to the greenhouse effect by converting trees to CO_2 and reducing vegetation available to store CO_2, also profoundly alters local and regional climates. This alteration can take several forms.

By removing vegetative cover, deforestation reduces the water retention capacity of the soil, increasing soil erosion and making lowland areas more vulnerable to flooding. Extensive deforestation appears to have been a large factor in continental runoff.

In addition, wide-scale deforestation appears to dry the climate of the surrounding region with studies suggesting such effects in parts of India, peninsular Malaysia, parts of the Philippines, Ivory Coast and the Panama Canal area and perhaps also in southwestern China, northwestern Costa Rica and northern Tanzania (Myers, 1988; Regie Newell, Salati, 1984-85). The local and regional climatic disruption, especially parching of agricultural lands, may be of much greater climatic impact to many areas than the changes produced by greenhouse-induced warming. Other human activities in addition to deforestation, eg drainage of wetlands, summer fallowing, bush clearing, and grazing of livestock, may also have regional climatic implications (Street, 1989).

1.3.4 Trends in stratospheric ozone depletion

There has been a certain decline of stratospheric ozone over the middle latitudes of the Northern Hemisphere in the past 20 years. The decrease in total column ozone between latitudes 30°N and 64°N has been 3% to 5.5% in the winter/early spring months since the late 1960s. Observations in the equatorial zone and Southern Hemisphere (aside from Antarctica where there has been pronounced ozone loss) are too sparse to be evaluated at this time (NASA, WMO Ozone Trends Panel, 1988; UNEP, 1989a).

Despite the certain ozone decrease, the information on the increase to date in biologically certain effects of UV-B radiation has been minimal. The major effects of the observed ozone reduction may occur in the winter months when, because of a low sun angle, UV-B radiation is normally low. Thus, the observed increases have been quantitatively quite small (WHO, 1989). Yet, even with full implementation of the Montreal Protocol to protect the ozone layer, it is projected that concentrations of chlorine in the stratosphere could roughly triple from their current levels of about 2.7 parts per billion (Hoffman and Gibbs, 1988). Furthermore, it is indicated that under certain conditions, significant ozone reduction may occur through heterogeneous reactions in such areas as the Antarctic.

UV-B radiation in the biologically active spectrum is projected to increase by at maximum 20-25% by 2050, but the projected depletion may vary by latitude (WHO, 1989). An increase of anywhere near this magnitude could have serious consequences for human health, forests, agriculture, the marine food chain and materials as indicated in Section 7 of this chapter.

Increased UV-B radiation resulting from stratospheric ozone depletion will interact with global warming to affect such concerns as air pollution, human health, vegetation, fisheries and natural systems. In addition, it is likely that expected further reduction of stratospheric ozone could have some direct impact on the warming itself by altering the atmospheric chemistry within the troposphere. Although it would hardly be surprising that a significant drop in stratospheric ozone could affect surface temperatures, it is not possible at this point even to be certain of the direction of this effect: whether it would magnify or reduce the projected rate of global warming. Increased UV-B radiation striking the surface of the ocean could, however, act to enhance the warming by reducing the biomass of CO^absorbing marine phytoplankton.

The one clearly understood interrelationship between global warming and stratospheric ozone depletion is the common role that man-made chlorofluorocarbons (CFC) and other ozone-depleting substances play in both processes. These compounds may provide as much as 25% of the current forcing towards global warming (Hansen et al., 1989) and are the principal cause of stratospheric ozone depletion.

1.3.5 Significance of rates of change

Even in the absence of such potentially additive or multiplicative local, regional or global effects such as urbanisation, desertification, deforestation and stratospheric ozone depletion, the projected pace of global warming is unprecedented in human history. Schneider (1989) points out that a climate change increase of 2°-10°F (1.1°-5.5°C) over a century, as projected by some emissions scenarios and models, is some 10 to 50 times faster than the average natural rates of change following the earth's recovery from the last ice age.

If the rate of change is sufficiently rapid, this change could overwhelm humanity's ability to adapt, triggering widespread refugee problems, famine and conflict over scarce resources. Moreover, capital equipment and facilities, such as buildings, industrial plants and civil works, each have design lifetimes after which replacement normally is expected. When the rate of climate change is sufficiently rapid and serious to necessitate abandonment or major modification before the end of the normal lifetimes of such investments, much greater economic costs may be incurred.

1.4 Potential impacts of human response: strategies to limit emissions of greenhouse gases

Humanity's growing concern over the political, economic and ecological consequences of rapid and large-scale climate change may itself produce major impacts on the energy, transport and industrial sectors, and result in changes in building design, land use, agricultural practices, and even in air pollution control.

Some sectors that will experience little impact from the direct effects of greenhouse warming, such as increased mean temperatures, changed precipitation and evaporation patterns, higher sea-levels and different storm patterns, may nevertheless be very significantly affected by public policies or consumer actions designed to restrain emissions of GHG. A particularly noteworthy example is the automotive industry. A rise of 3°C or 4°C in mean global temperatures would require only little adaptation in engine design given the wide tolerances already engineered into cars; yet public concern about GHG emissions may lead to more stringent fuel economy standards, taxes on carbon-based fuels, consumer movement to smaller or more fuel-efficient vehicles, and public policies or consumer shifts favouring alternative fuels in place of gasoline, and shifts from private automobiles to mass transit.

Concern over the growth of GHG emissions could lead to public policies increasing taxes on gasoline or other fossil fuels, or institution of a carbon tax, levying higher relative charges on such high carbon-content fuels as coal compared with natural gas. Such policies could produce some shifting among fossil fuels, penalising coal producers while increasing markets for gas producers. Regulatory and tax policies designed to limit emissions of GHG gases could create greater market opportunities for energy conservation technologies and non-carbon-based fuels such as solar, wind, geothermal, ocean thermal, hydrogen, fission and fusion.

Governmental policies initiated in response to greenhouse effect concerns also may have impacts on the structure of energy investment. Response strategies to greenhouse effect concerns may cause some countries to choose more reliance on nuclear power and others to rely more on renewables, more energy-efficient fossil-fuel technologies, or shifts among types of fossil fuels. Non-climate-related environmental factors may also act as constraints on rapidly increased reliance on non-carbon energy systems such as hydroelectric power or nuclear power. Increased construction of hydroelectric projects may require considerable human resettlement and flooding of important ecological resources. A serious constraint on increased reliance on nuclear power will be the satisfying of public concerns regarding plant safety and adequacy of waste disposal. Analysis of response strategies and their implications have been undertaken within Working Group III.

Concerns in the US in the mid 1970s over potential depletion of the stratospheric ozone layer led to a sharp drop in sales of CFC aerosols well before the US Environmental Protection Agency in March 1978 prohibited the production and use of non-essential aerosols. Once consumers had been widely aroused by news reports of the CFC threat to the ozone layer, producers of non-CFC aerosols and alternative delivery systems such as pumps and hydrocarbon-propelled sprays aggressively and successfully marketed the environmental advantages of their products. (EPA, June 15, 1988 Regulatory Impact Analysis; Kavanaugh et al., 1986.)

It appears too early to detect any pronounced shift in consumer choices in response to concerns about greenhouse emissions. Yet environmental and public groups are promoting product or fuel shifts partly out of concern over emissions of GHG.

The renewable energy industry and energy conservation technology industries are likely beneficiaries of the growing public concern about climate change. Consumer interest in environmentally benign technologies may stimulate their growth. Already some public interest groups are circulating catalogues indicating where consumers can purchase non-CFC refrigerators and a variety of energy saving products.

International treaties, government regulatory policies, shifts in consumer preference for products, and changes in public and private sector investment patterns may all result from growing public concern over the threat to humanity posed by rapid global warming. These responses may produce major impacts on significant sectors of society, but aside from the studies under way within Working Group III there is little analysis allowing such potential effects to be quantified. Accordingly, other sections of this chapter will focus largely on such direct effects of climate change as changes in temperature, precipitation, wind, storm patterns, sea-level and UV-B radiation. A high priority of climate impacts research and analysis should be the assessment of the potential magnitude and direction of alternative response strategies to address climate change.

2 Summary of likely impacts of climatic change on human settlement

Among the most significant of all the potential impacts of climate change are the possible effects on human settlement, a broad term meant to encompass (i) housing or shelter, (ii) the surrounding community, neighbourhood, village or relevant social unit in which individuals live, (iii) the supporting physical infrastructure (eg water and sanitation services and communications links) and (iv) social and cultural services (eg health services, education, police protection, recreational services, parks, museums etc). Several areas, eg energy, transport, industry and human health, each of which is a central concern of human settlement, will be addressed separately in some detail in subsequent sections.

2.1 Scope and limitations of the assessment

There are relatively few studies on the likely impact of climate change on communities, other than some studies of likely implications of sea-level rise.

A principal difficulty in constructing studies of the likely impact of climate change on human habitat is the fact that many other factors largely independent of climate change, eg demographic trends, technological innovation, evolving cultural tastes, employment opportunities and transportation modes, may significantly shape where and how people will choose to live in the future. For purposes of constructing a model, it is convenient to hold all other factors equal while varying only climate. Yet as Timmerman (1989) points out, virtually the only thing we can be sure of is that all other things will not remain equal.

One can reliably predict that certain developing societies will be more vulnerable to climate changes than highly industrialised countries because they are already at the limits of their capacity to cope with climatic events. Tropical cyclones such as Hurricane Gilbert that ravaged Jamaica in 1988, the floods that inundated large portions of Bangladesh in 1987 and 1988, and the drought-induced famine that has plagued parts of Africa over the past decade are all manifestations of the extraordinary present vulnerability of many developing countries to extreme climatic events.

2.2 Assessment of impacts

2.2.1 An overview of potential vulnerability of human settlement to rapid climate change

Although there are few analyses of such potential impacts, there is every reason to believe that if climate change were to occur at the high end of the projected ranges, the consequences could be serious for many countries, especially for developing countries.

The very existence of entire island countries such as the Maldives, Tuvalu and Kiribati could be imperilled by a rise in the mid range of current sea-level rise projections. Such a sea-level rise could also cause large population displacements in the river delta regions of such densely populated nations as Egypt, India, Bangladesh and China (Tickell, 1989). Although studies of the likely impact of climate change on agricultural production in developing countries are quite sparse, such agriculture is quite vulnerable to climatic variability, and much present hunger and malnutrition in Africa may already be attributable to drought-induced famine.

Changes in climate could produce large impacts on nomads and traditional societies, such as Canadian Inuit people (Amagoalik, 1989), the Gwichin people of Canada's Northwest Territories and Yukon Territory, where climate change may adversely affect hunting, trapping and fishing, which are central both to the economy and the culture of the Gwichin people (Kassi, 1989). Warming in the Arctic and sub-Arctic could mean a shorter trapping season and reduced quality of furs, a major source of income for many Yukon Territory residents (Klassen, 1989). With Working Group I having projected that an effective CO_2 doubling could produce a warming of 2°-5°C in winter and 3°-5°C in summer in the southern Sahara, it appears plausible that inhabitants of that region, many of whom are nomads, would be significantly affected by such changes in an already hot climate, but little systematic study has been done to identify the potential effect of climate warming on nomadic peoples in hot regions such as the Sahara or the Arabian Peninsula.

Studies do exist, however, in several important areas. These include:

2.2.1.1 Vulnerability of human settlement to sea-level rise

A i m sea-level rise is likely to cause major problems on the intensely utilised and densely populated Asian coastal plains - producing coastline recession of up to several kilometres, displacing coastal villages and depriving many people of their land and resources (Bird, 1986). A group of experts convened by the Commonwealth Secretariat (1989) reported that important river deltas that are likely to be seriously affected by climate change include 'the Nile in Egypt, Ganges in Bangladesh, the Yangtze and Hwang Ho in China, the Mekong in Indo-China, the Irrawaddy in Burma, the Indus in Pakistan, the Niger in Nigeria, the Parana, Magdalena, Orinoco and Amazon in South America, Mississippi in US and the Po in Europe' (at p67). Major coastal erosion problems are likely in South America at population centres such as Rio de Janeiro, Brazil, and Mar del Plata, Argentina, (Leathcrman, 1986). In an analysis of implications of sea-level rise on four Pacific atoll states, Kiribati, Tuvalu and the Marshall Islands (all independent nations) and

Tokelau (a territory of New Zealand), Roy and Connell (1989) project the drowning of barrier reefs, intrusion of saltwater into coastal groundwater supplies, erosion of flat land, and storm damage to ports and other coastal facilities.

Significant sea-level rise could cause considerable damage to the southeast coastal zone of China, that country's most developed agricultural and industrial area. There is a possibility of the flooding and destruction of most of the existing salterns and seawater farms, which are important food sources for China's coastal cities. Wide-scale destruction is projected along the more developed areas on the Yangtze River and Yellow River, with loss of at least 10 million tons of grain. Additional potential adverse effects include damage to housing, transportation and water supply, and expansion of salinised land with destruction of the coastal ecological environment and environmental protection facilities (Ye, 1990).

A i m sea-level rise could inundate 12-15% of Egypt's arable land and 11.5% of the land of Bangladesh (Broadus et al., 1986). Sea-level rise already threatens the historic Kenyan town of Lamma (Odingo, 1989). Preliminary findings of a survey by the Ministry for Population and Environment indicate that a i m sea-level rise would produce wide-scale population displacement in Indonesia. A case study of such impacts on the coastal areas found significant population displacement in each of the three regencies surveyed. In Bekasi Regency such a sea-level rise would flood about 7000 ha of brackish water fish area, 10,000 ha of food crops would be damaged by saltwater intrusion, and 3300 households would lose their land. At Karawang Regency this sea-level rise would flood about 11,000 ha of brackish water fish area, damage 50,000 ha of agricultural land through saltwater intrusion and deprive at least 80,000 households of their livelihood. A i m sea-level rise at Subang Regency could flood about 7000 ha of brackish water fish area, damage 20,000 ha of rice-producing wetlands and 6000 ha of home gardens, and destroy the livelihoods of about 81,000 farmers (Sugandhy, 1989). Recently, India has launched a major program for study of the impact of sea-level rise due to the greenhouse effect along the coasts and islands of India. UNEP is sponsoring similar studies of the coasts of West Africa and East Africa.

2.2.7.2 *Vulnerability of human settlement to tropical cyclones*

As sea surface temperature rises, the ocean area which can spawn tropical cyclones (typhoons, hurricanes etc) is expected to increase. Although the area of sea having temperatures over this critical value will increase as the globe warms, the critical temperature itself may increase in a warmer world (Working Group I Report). Some scientists argue that the intensity of these storms may increase (Emanuel, 1987). One severe storm in September 1988, Hurricane Gilbert, is estimated to have caused eight billion dollars damage in Jamaica alone (Topping, 1988). Damage by tropical cyclones is a major impediment to economic development throughout the Caribbean region and can be expected to become an even larger factor if storm damage increases (Granger, 1989). Tropical cyclones also pose major threats to industrialised nations, as occurred when Hurricane Hugo in September 1989 wreaked havoc along the Carolina coast of the US.

2.2.1.3 *Vulnerability of human settlement to flood*

Floods are already a major ongoing concern of many developing countries and this problem may be exacerbated by global climate change. Some climate model projections suggest that the greenhouse effect will enhance both ends of the hydrologic cycle, producing more instances of extreme rainfall as well as increased drought (Hansen et al., 1989; Golitsyn, 1989). Thus, floods may become an even greater threat as the world warms. In some instances, the expected rise of sea-levels may aggravate the vulnerability of coastal countries to floods. The floods of 1987 and 1988 proved very damaging to Bangladesh, forcing millions of people from their homes for long periods of time. Yet the people of Bangladesh showed a remarkable resiliency in responding to the 1988 flood, which inundated a large portion of the country (Safiullah, 1989), and this ability to adapt will be increasingly important to coastal countries that will experience increased inundation even under a low climate change scenario.

2.2.1.4 *Vulnerability of human settlement to drought or water shortages*

Another section of Working Group II is developing detailed projections of likely availability of water resources in a warmer world. The present literature suggests that drought may become a much greater problem. Hansen et al. (1989) foresee drought conditions occurring 5% of the time in the control run (1965 to relatively recently), rising to 10% in the 1990s, about 25% in the 2020s and about 45% in 2050. An Indonesian government study of $C0_2$ doubling and its effect on three river basins, the Citarum River Basin in West Java, the Brantas River Basin in East Java and the Saddang River Basin in South Sulawesi, projected much faster runoff, widescale soil erosion and much lower water production.

(Sugandhy, 1989.) Such a loss of water resources could be expected to have considerable impact in Indonesia, population of which is increasing rapidly.

Global warming may be expected in some regions to lower the groundwater level, decrease the surface of many lakes or inland waterways, and drop the water level of such bodies. Major disruptions such as those experienced in the Lake Chad region of Africa could become a greater problem. Some other regions might benefit from more abundant water, but accurate prediction of such regional impacts is difficult at this point.

Farmers' responses to drought and land degradation may take many forms. Adaptation to drought may include agro-pastoral management techniques providing for a more efficient use of reduced rainfall. Poverty and hunger resulting from drought may cause migration and degradation, or change of diet. Land degradation may produce either abandonment of the land or, where investment capacity and knowledge are available, change in cultivation practices to improve yields and arrest land degradation (Mortimore, 1989).

2.2.1.5 Vulnerability of human settlement in some countries to loss of biomass

A major threat to developing countries posed by global warming may be acceleration of depletion of biomass cover as a result of increased drought. This could be an especially severe problem in Africa, where energy supply for 40-odd oil importing countries comes from biomass to a very large degree: upwards of 80% in most countries and over 90% in some (Tebicke, personal comment, 1989). Africans, the majority of whom depend on biomass also for housing, furniture, implements, utensils etc, could experience greater scarcity for such uses.

2.2.1.6 Vulnerability of human settlement to rapid thawing of the permafrost

Climate models have generally projected that arctic and subarctic areas are likely to warm more rapidly than the average global temperature increase. Such a rapid warming could result in a significant thawing of the permafrost in the subarctic, producing major disruption to buildings, roads and bridges, adversely affecting the stability of some existing structures and forcing changes in construction practice (French, 1989).

Permafrost areas of China, which account for about 18% of that country's total territory, appear highly vulnerable to thawing, according to a recent Chinese government assessment. This permafrost zone is mainly distributed in Quinghoi, Tibet Plateau, Quilianshon Mountains, Tionshon Mountains, Altai Mountains, Doxirganling and Xiaoxingongling Mountains in northeast China, and Inner Mongolia. The layer of permafrost is located normally at 1.5-5.0 m in depth and is about 0.5-2.0 m thick (Ye, 1990).

If the temperature were to rise by 0.5°C and remain stable for 10-20 years, it is projected that about 5% of the permafrost in China would thaw out, while a 40-50% thawing is projected for a 2°C rise over 10-20 years. Projected impacts of such a thawing include a large a area of thaw settlement and slope landslide with destruction of highways, railways and housing built on permafrost (Ye, 1990).

2.2.1.7 Vulnerability of human settlement to health problems associated with climate change

Climate change may threaten the health of large numbers of people. Flooding and storm surges associated with sea-level rise could increase the incidence of water-borne diseases. Opportunistic diseases could afflict those weakened by famine or malnutrition. Wide-scale disruption of communities could include psychological stress among environmental refugees. Degradation of water quality or sanitation faculties could put more pressure on public health faculties. These and other health effects are discussed in more detail in Sections 2.2.3 and 6.

2.2.2 Implications of climate change for economic activity

Owing to the complexity of developed countries and the fact that many factors largely independent of climate change - employment changes, technological innovation, changes in terms of trade and currency values, and land use policies - will affect human habitat, it appears quite difficult to isolate changes which are due to global warming from other changes that might occur. Some assessments exist in the following two areas:

(i) Modification of supplies and consumption patterns

Climate change can be expected to have differential regional impacts on the supply and cost of various types of food and fibre, and on availability of water. This changing availability of resources could be reflected in changed diets, production patterns and employment levels. One study has projected that an effective CO_2 doubling could produce a major water shortfall for New York City equal to 28-42% of the planned supply in the Hudson River Basin. The least expensive means of adding this capacity, it is calculated, would be a $3 billion project to skim Hudson River floodwaters into additional reservoirs (Miller, 1989).

(ii) Changes in the physical and social environment

The physical environment may be transformed as a result of direct effects of climate variability:

- loss of property from natural disaster including storm surge that would be aggravated by sea-level rise. (This is a particularly significant factor in the Caribbean region (Granger, 1989) and has recently contributed to huge losses in the southern US as well.)

- effects of weather variables on housing and street conditions. An effective CO_2 doubling is expected to save the American city of Cleveland, Ohio, $US4.5 million annually in reduced snow and ice removal costs and $700,000 per year from reduced frost damage to roads and bridges. Yet the same study projects that global climate change, largely sea-level rise, would require at least $600 million in additional public sector capital investment in the Greater Miami area of Florida over the next century. A i m sea-level rise would require raising most bridges to ensure sufficient under-clearances. Such a sea-level rise could infiltrate the base of about a third of the streets of Dade County, Florida, necessitating added public reconstruction costs of $250 million and large additional costs to building owners to improve drainage, raise yards and pump sewage to mains (Miller, 1989).

- effects on construction materials. The same Urban Institute study of added infrastructure needs in Cleveland, Greater Miami and New York City associated with climate change found minimal effects on sewer pipe corrosion in Miami, and annual reductions, in 1987 US dollars, of $700,000 in frost damage to roads, $500,000 in road maintenance and $200,000 in road reconstruction, all in Cleveland. An analysis of impacts of climate variability on construction in the UK notes that high humidity and high temperatures weaken alumina cement, and low humidity and high evaporation rates lead to plastic cracking of concrete (Parry and Read, 1988). Air pollution poses threats to metals and other building materials (Graedel and McGill, 1986). Should climate change exacerbate air pollution, these materials effects could increase.

- stress on sewerage and septic waste systems resulting from increases in frequency of storm-water surcharging and potential overflows.

- increased life of vehicles and other metal objects owing to reduced use of salt for snow and ice mitigation (Goklany, personal communication, 1989).

There is a wide number of potential indirect effects that may follow changes in climatic variability. These include:

- potential abandonment or relocation of industrial sites as a result of climate change. Changes in availability of natural resources, particularly water, may affect the viability of industrial facilities that are dependent on such resources.

- changes in traffic resulting from climate-induced changes in transport modes. Water resource changes could reduce or increase use of barge traffic, thereby changing traffic on competing transport modes such as railways or roads.

- changes in building design to accommodate to climatic change. These could include road layout affecting the placing of buildings, greater use of new, more weather-tolerant materials and greater attention to landscaping to reduce the urban heat-island effect.

2.2.3 Migration and resettlement

Migration and resettlement may be the most threatening short-term effects of climate change on human settlements. People may decide to migrate in any of the following cases:

- loss of housing (because of river or sea flooding or mudslides);

- loss of living resources (like water, energy and food supply or employment affected by climate change);

- loss of social and cultural resources (loss of cultural properties, neighbourhood or community networks, particularly in the case of a devastating flood).

In developing countries, changes in commodity prices or foreign trade practices may trigger large-scale migration. The declining demand for natural rubber reportedly caused significant migration in Thailand, Malaysia and Indonesia (Simmons et al., 1977).

Migration may occur following a decline in living standards or a total loss of livelihood following land degradation (itself possibly due to an earlier migration toward marginal land unable to support over-cultivation) or a major 'natural' disaster like flooding or drought. The vulnerability of human settlements to climatic events is particularly great in developing countries, where high population densities and growing urban congestion are likely to increase the sensitivity to and potential magnitude of natural disasters.

'Environmental refugees,' people displaced by degradation of land, flooding or drought, are becoming a much larger factor in many developing countries (Jacobsen, 1989; Tickell, 1989; Debrah, 1989). Even a modest rise in global sea-levels could produce tens of millions of such refugees. Population movements from blighted agricultural regions could result in areas where crop productivity may be cut by prolonged drought or temperature stress on vulnerable crops.

Resettlement itself raises considerable new problems for newcomers and possibly for local inhabitants. In cities, it places additional burdens on existing housing, medical care facilities and various essential urban services and infrastructure. From the point of view of health, migration and resettlement could cause the following situations to occur in developing countries (modified from Lee, 1985):

- Insufficient capacity of health services and lack of physical or economic access to them;
- Sanitary facilities and housing could become quickly overburdened in the receiving area, enhancing the spread of communicable diseases;
- Both residents and newcomers may be exposed and susceptible to new diseases (introduced by new arrivals or inversely);
- More directly, resettlement is known to be the cause of psychological strains (loss of connection with the original land and traditions) further inducing health problems.

In economically advanced industrialised countries, migration is a likely social and cultural response of specific population groups to new physical and social environments produced by climatic change. Forced migration and resettlement would be the most severe effects of climatic change as a result of natural disaster and loss of employment.

Natural disaster (particularly flooding) is likely to occur in some areas as a result of climatic conditions. Moreover, local communities may be induced to migrate by the policy choice of no response to sea-level rise in particular areas of developed countries.

Changes in production systems may lead to industrial relocation or employment reductions. Migration may be a preferred response to threatened loss of housing or employment.

2.3 Determination of sensitivities

2.3.1 Factors enhancing sensitivity to the impacts

In developing countries, climate change should be a major cause of damages to human settlements for two reasons:

- the high dependence on food supply and agricultural production, which is highly sensitive to climate change;
- the inability to respond to major impacts like sea-level rise or flooding while the magnitude of impacts in these particular areas will be high (Tickell, 1989).

The sensitivity of developing countries to impacts on human settlement through land degradation and natural disasters is already evident in some countries: flooding in Bangladesh in 1988, monsoon failure in India in 1987, progressive desertification in Sahel countries.

Important and significant trends able to slow down or aggravate the effects of climate change on social and economic restructuring are the following:

- Industrialisation and over-urbanisation;
- Population increase, urbanisation and industrialisation in the developing world will combine with climate change to produce significant societal changes;
- In developed countries, economic changes of recent years have generally led to significant spatial and urban changes. First, some places are in decline (abandoned former industrial sites, some forms of housing, urban zones). Second, enterprises as well as individuals are more sensitive to the quality of the living environment (housing, medical care, social services, culture, recreation and climate itself) (see Ministère de l'Equipement, du Logement, de l'Aménagement du Territoire et des Transports, 1986, modified). The communications revolution and computer and FAX technologies may permit greater decentralisation of the population by enabling many professional and technical people to perform work in homes far removed from major metropolitan centres.

2.3.2 Spatial and social differentiation

Climate change could translate into migration of impoverished people from rural to urban areas (developing countries), from coastal lowlands (particularly densely inhabited delta areas) to inland areas, and possibly across national boundaries.

The most vulnerable populations are those exposed to natural hazards. In 2050, habitable land could be lost for 16% in Bangladesh and 15% in Egypt. Population displaced would amount to 13% and 14%, respectively (Jacobson, 1989).

In developing countries, the most vulnerable populations are farmers engaged in subsistence agriculture, residents of coastal lowland, populations in semi-arid grassland, and the urban poor pushed back into squatter settlements, slums and shanty towns. Urban population growth is the highest in Africa, the urban population of which should double between 1980 and 2000. Population and urbanisation increases in developing countries in general will generate impacts on natural resources and the environment which are likely to increase sensitivity to climate change. Vulnerable populations should primarily be the elderly and low income households which may face higher costs for supplies, facilities and essential services.

2.4 Tasks for the near future

Some important priorities may be defined. First, reliable projections of human settlement implications of climate change should relate to specific climate models, none of which can yet provide reliable projections of likely future local climates. Improvement of the grid resolution of the GCMs would seem essential to permit correlation between likely local climate scenarios and potential impacts. Climate change impact analyses are especially scarce for Latin America which contains regions highly sensitive to climatic fluctuations associated with such phenomena as El Niño. Second, the complex linkages between urban functions likely to be affected by changed weather conditions and altered urban settlement patterns in developed countries are not well understood, and these interactions may vary considerably in different geographic areas, eg central cities, secondary cities, suburbs and rural areas. In developing countries, many largely non-climatic factors, eg improvement of agricultural management, increased urbanisation, and self-reliance, may produce very different impacts in urban and rural areas. Third, the relationship between urban, social and economic changes and climatic effects needs to be quantified. Finally, study needs for the effects on building materials and design of buildings have been described by Parry and Read (1988).

The most difficult task is to correlate analogical studies (assessment of effects from historical and geographical analogies) with the future climate change projections. This should in addition take into account the effects of policy trends (housing and social policies, energy policies etc). The need to consider the feedback of policies developed to address social and economic problems constitutes a serious difficulty in correctly assessing the expected impacts of climate change on human settlements.

3 Summary of likely impacts of climate change on the energy sector

3.1 Scope and limitations of the assessment

3.1.1 Definitions

Energy includes all controllable forms of energy used for heat, power and processes in human activities: electricity, fossil and other fuels, nuclear power, hydroelectric power, biomass, animal power, solar, wind etc. Energy sector impacts mean the effects of climate change in changing demand, prices and availability of energy commodities, and in altering the function of all parts of energy supply and use systems: exploration, extraction, conversion, distribution and consumption of energy.

3.1.2 Geographic and substantive scope

This section deals with available information on potential impacts on energy supply and consumption due to assumed global climate change. Energy supply and prices may be affected through impacts on the supply system and also through secondary effects of impacts that alter demand for energy, eg decreasing demand for heating and increased demand for air-conditioning. Primary, secondary and higher orders of impact refer to the relative stage of the cause-effect chain starting with primary effects directly connected with changes in climate variables (ie temperature, precipitation, wind and other atmospheric variables, plus changes in ocean variables such as temperature, currents and sea-levels). Secondary and higher order effects are not necessarily less important than primary effects, but they are typically more difficult to estimate with precision. Indirect impacts on energy activities due to policy responses to climate change are only briefly discussed, but potentially they might be important. These impacts are considered by Working Group III.

Because of the sparse treatment of this topic in available literature, quantitative information on impacts primarily is limited to changes in electricity demand for three industrialised temperate zone countries with and without climate change at levels predicted by the GISS GCM (Smith and Tirpak, 1989; Nishinomiya et al., 1989; Parry and Read, 1988). Another case study of impacts on energy use for heating and air-conditioning in a fourth temperate country, West Germany (FRG), also is discussed (Gertis and Steimle, 1989). Impacts of changes in water availability on hydroelectric power also have been estimated for several sub-national regions (ICF Inc., 1987; Smith and Tirpak, 1989; Singh, 1988).

Additionally, recent trends in electricity and direct heat use in developing countries are provided in order to give qualitative statements as to the probable degree to which current use may be affected by potential climate change (Meyers and Sathaye, 1988; Sathaye et al., 1989).

Finally, a set of comments extracted from the literature and discussions of the panel concerning unquantified and secondary impacts on energy and electricity production is provided; these include primary supply impacts due to accelerated sea-level rise and potential extremes in weather, plus secondary impacts due to changes in water supply and biomass production (Smith and Tirpak, 1989; Nishinomiya et al., 1989; Tebicke, 1989).

3.1.3 The relationships of expected impacts

Figure 5.1 provides a system flow chart of how changes in climate parameters can affect energy supply and demand, resulting in impacts on energy supply and cost. As the figure indicates, demand can be increased or decreased by temperature increases according to season, and reliability of energy supply may be reduced unless additional reserve capacity and protection from severe weather incidents are provided. Most changes indicated in Figure 5.1 can occur in either direction; for example, increased regional precipitation could increase the potential for hydroelectric power generation and biomass fuel energy. Many potential impacts are not shown in Figure 5.1. The choice among fuel forms and among energy sources, including alternate energy sources such as direct solar, hydro and nuclear, may be constrained; added capacity, especially peaking capacity and the associated additional capital and higher operation costs, may be required. Existing and potential biomass energy supply and use, of special importance in many developing countries, may be reduced by decreases in soil moisture or inundation of agricultural land by sea-level rise. This would force countries to spend capital and operating costs to substitute alternative energy sources or conservation measures. (Biomass impacts are addressed by other sections of Working Group II, but these indirect impacts on energy are noted here for completeness.)

Most of these impacts are typically not likely to result in absolute constraints on energy supply systems, but the magnitude and the rate of the added demands and constraints need to be considered with a full representation of uncertainties of the global climate change forecasts. Climate-related reductions in limited energy sources such as biomass and hydroelectric power, combined with other stresses, might constrain availability of these resources. Non-climate-related environmental factors may also act as constraints on rapidly increased reliance on non-carbon-based energy systems such as hydroelectric power or nuclear power. Increased construction of hydroelectric projects may require considerable human resettlement and flooding of important ecological resources. A serious constraint on increased reliance on nuclear power will be the satisfaction of public concerns regarding plant safety and adequacy of waste disposal.

3.2 Assessment of impacts

3.2.1 Industrial country energy demand

The principal quantitative analyses of energy impacts have been carried out using the US' and Japan's electricity supply and demand case studies under conditions of no assumed climate change contrasted to global climate change as predicted by the GISS models (Smith and Tirpak, 1989; Nishinomiya et al., 1989). Studies of the effect of temperature change on electricity demand have also been made in the UK (Parry and Read, 1988) and on end-use energy in the FRG (Gertis and Steimle, 1989). In the US this includes results for the year 2010 and 2055; the preliminary Japanese study considers conditions for the year 2000 but with an equivalent temperature change predicted due to a doubling of CO_2 concentration, a condition similar to the US 2055 forecast. The study of FRG on the energy demand for heating and air-conditioning contrasts space heating and air-conditioning energy use in 2030, with and without a climate change of 1°C temperature increase and technology improvements in insulation. A USSR assessment has been made of heating costs in a changed climate. These studies suggest for these five temperate-climate, industrialised countries the following:

- Demand for electricity over the next 60 years without climate change will more than double for the US. The incremental rise in electricity demand due to climate change would increase capacity requirements by 14% to 23% on a national basis. This would require added investments of approximately 10% in the global climate change case as compared to needed investment expected without climate change (Smith and Tirpak, 1989; ICF Inc., 1987).

The results for the US in 2055 and for Japan with a 3°C temperature increase, using monthly electricity demand for year 2000, suggest that annual electricity demand would increase 5% to 10% for global climate change compared to expected demand without considering this effect (Smith and Tirpak, 1989; Nishinomiya et al., 1989).

In the US there is considerable regional variation from the national averages. In northern regions a slight decrease in annual generation may occur owing to a decrease in winter demand for electricity. This reduction could exceed the increased demand in warmer seasons for electricity for space cooling. (Net electricity changes depend in part on the fraction of space heating served by electricity.) In the southern regions where a much lower heating demand occurs, annual electricity demand can increase up to 15%. Since much of the added demand is in peak periods, these southern regions may require an added capacity requirement of up to 30% while some northern regions would require slightly less of a capacity addition than would be required in a no-climate-change scenario (Smith and Tirpak, 1989; ICF Inc., 1987).

Temperature and wind speed dominate heating demand in the UK, but cloud and fog largely determine the demand for artificial day-time lighting. Precipitation, especially snow, is an important factor in electricity demand (Parry and Read, 1988).

The FRG study (Gertis and Steimle, 1989) indicates that climate warming is likely to produce a substantial decrease in German energy demand for space heating. A temperature rise of 1°C is projected to reduce energy consumption for heating purposes by only 13% of older single family homes and by 45% in new homes. The results for multi-family structures are an 8% reduction in heating consumption for older structures and 67% for new buildings. However, potential decreases in energy demand due to improved building technology are much larger than decreases due to a climate warming of 1°C. Increases in air-conditioning demand depend strongly on the unknown, but highly influential, change in humidity; an assessment shows that the corresponding increases of energy consumption for air-conditioning will range between 12% and 38%. Hence, humidity is an important parameter to determine in climate change predictions. However, air-conditioning energy demand is much smaller than heating demand in the FRG, so there would be a decrease in energy demand for space heating and air-conditioning by 12% in the year 2010, the earliest year a 1°C increase was projected. In comparison with today the energy demand will decrease by 9%. The corresponding results for CO_2 emissions from these sectors are projected as a 10% reduction in 2010 and a 12% reduction compared with present emissions.

- An increase of 1°C or more of temperature in the USSR would be expected to produce savings in heating costs for the areas from Moscow northward. Heating savings in the winter season would outweigh some modest additional costs for summer air-conditioning (Vladimirova, 1990).

- Climate change may increase investments and operating costs for electric utilities, but these incremental additions appear to be smaller than other additions that will be made even if global change is ignored (Smith and Tirpak, 1989). Electric utility planners should consider climate change when planning new capacity and operations. However, the estimated impacts of climate change are similar to the range of other uncertainties that these planners traditionally have considered.

3.2.2 Developing countries' electricity demand

In 12 of the more energy-intensive developing countries studied by Meyer and Sathaye (1988) the residential and commercial demand in 1986 was 28%

Table 5.1 Sectoral shares of electricity consumption, 1970-1986 (%)*

Combined data for twelve developing countries	1970	1980	1986
Industry	63	60	59
Residential	16	18	19
Commercial	9	10	9
Public	7	7	7
Agriculture	4	5	6
Transportation	1	1	1

* From Meyers and Sathaye, 1988.

(see Table 5.1.). In Japan, in contrast, use of electricity in commercial and residential facilities in 1987 was about 55% of total usage (Nishinomiya et al., 1989). There is wide contrast in this share among countries. Based on unconstrained electricity use scenarios estimated by US EPA in the year 2025, rapid growth in the developing countries would result in expanded electricity use of over 50%, and the residential commercial part of the growth would be slightly less than the 1986 figure - 22% (Sathaye et al., 1989).

Therefore, although the developing countries, as projected by the Sathaye et al., 1989 forecast, may have substantial investment needs to meet the projected demand for electricity, the fraction of this demand that is related to temperature change remains much smaller than the fraction expected in an industrialised nation. The added increment for developing countries should be less than 10%, again a small but added uncertainty for utility planners compared to the demands placed on the same planners without consideration of climate change.

3.2.3 Implications for demand by particular utilities

Examining three electric utilities, one in upstate New York, one in downstate serving the New York City metropolitan area and one in the southeastern United States, Linder and Gibbs (1988) project that a summer temperature increase of about 0.8°C would cause an 0.96% to 2.14% increase in peak demand and an 0.27% to 0.21% decrease in primary energy use for the upstate New York utility, and a 2.20% to 4.04% increase in peak demand and an 0.49% to 1.04% increase in energy demand for the downstate New York utility. Projecting an increase in summer temperature of just over 1°C, they projected a 7.04% increase in peak demand and a 3.4% increase in total energy demand.

In an examination of regional and national climatic effects of climate change on demands for electricity in the US, Linder (1989) projects that new capacity requirements would increase 9-19% or about 25 to 55 gigawatts (GW) using GISS Model B for 2010. The majority of the capacity increase would be for peaking capacity rather than for baseload capacity. The largest regional impacts are anticipated in the southeast and the southwest where air-conditioning is a major use of electricity.

Parry and Read (1988), in a study of energy demand in the UK, report:

> Demand for energy increases progressively as temperatures fall below 18°C. For example, demand on the Central Electricity Generating Board (CEGB) in the U.K.increases by one percent (400 MW) in response to a temperature fall from 1°C to 0°C; larger increases occur for a one degree fall in colder conditions (at pp. 37-38).

Parry and Read project that an increase in windspeed from 5 to 15 knots at 2°C raised UK demand by 700 megawatts (MW).

In a detailed study of public buildings in Cleveland, Ohio, US, Miller (1989) projected that in a CO_2 doubling scenario heating cost for public buildings could drop an estimated $2.3 million per year while public air-conditioning costs could rise by $6.6 to $9.3 million annually.

It would appear that global warming would have very different effects on energy demand, raising it in areas where air-conditioning is a driving factor in such demand and sometimes reducing demand where heating is a more dominant use.

3.2.4 Implications for availability of hydroelectric power

By changing water resource availability, climatic change could affect the hydroelectric power industry, producing quite different effects in various regions. Based on the US impact studies (Smith and Tirpak, 1989; ICF Inc., 1987), a major concern is the availability of water on a sustained basis for natural systems, irrigation, domestic needs and hydroelectric generation plants. GCMs predict considerable variability in total annual water supply and, for many areas, changes in levels of relative seasonal supply. As shown in Table 5.2, the fraction of domestic electricity demand met by hydroelectric power varies considerably among countries in all categories of industrialisation. (See Table 5.2 for some examples.) The changes that may occur to the potential electricity supply from this energy source could be considerable for many countries if the annual or seasonal variations cause significantly lower water reserves.

Examining implications of climate change for Quebec under an effective CO_2 doubling, Singh (1988 given) projects a potential increase in hydroelectric generating capacity of about 93,000 GW hours. On the other hand, Sanderson (1987) estimates that for the Canadian hydroelectric generating stations on the Great Lakes, climatic change plus greater consumption could result in a loss of 4165 GW hours of power generation.

Table 5.2 Shares of public electricity generation in 1986 by power source* (%)**

Country	Oil	Gas	Coal	Hydro	Nuclear
China	14	1	65	21	-
India	5	4	60	29	3
Indonesia	66	2	-	25	-
Malaysia	56	19	-	25	-
Pakistan	14	30	-	54	2
Philippines	36	-	9	31	-
South Korea	19	-	31	6	44
Thailand	13	41	21	22	-
Argentina	16	23	1	47	13
Brazil	4	-	2	94	-
Mexico	57	10	7	22	-
Venezuela	20	30	-	50	-
Nigeria	3	65	-	31	-
Egypt***	46	27	-	28	-

* Adapted from Meyers and Sathaye, 1988.

** If self-production were included, the share of oil would be larger, considerably so in some countries. It was not included here because of uncertainty regarding the data.

*** 1985

In Norway, it has been projected that hydroelectric power energy production may increase 2-3% under an effective CO_2 doubling. This is partly due to an increase to the inflow of the reservoirs, but also due to reductions in the overflow spill. The seasonal distribution of the runoff is projected to correspond more closely with consumption, thus producing increasingly reliable power yield (Norwegian Delegation, 1990).

The major energy-using developing countries presently get much of their electricity from hydroelectric generation. For some countries electric energy from present sources may be severely reduced. Because of the capital intensiveness of hydroelectric power and the fact that many developing countries invested in it in response to the oil price escalation of the 1970s, they are particularly vulnerable to reductions in hydroelectric energy potential. Other countries also need to consider possible climate impacts on hydroelectric power supply, especially regional impacts. Substantial shifts in the price and availability of hydroelectric power could affect the competitive position of manufacturing industries that depend on such power as a major factor in production.

3.2.5 Other potential impacts

Recent studies of impacts of energy caused by climate change also have identified the following impacts without providing detailed analysis:

- If water supply to a thermal power plant is reduced, the dissipation of waste heat may require use of more costly water or a change in the technology to dissipate the heat (Smith and Tirpak, 1989; Nishinomiya et al., 1989).

- If greater variation in extreme weather events occurs, transmission and distribution systems susceptible to interruption due to storms may need to be 'hardened' at increased cost or customers may have to accept less reliable service. (Smith and Tirpak, 1989; Nishinomiya et al., 1989).

- Sea-level rise can require added expenditures at present coastal power plant sites for new or added barriers from rising waters and may reduce acceptable sites for future thermal power plants (Smith and Tirpak, 1989; Nishinomiya et al., 1989).

- Increases in regional cloudiness or decreases in prevailing wind intensity can reduce the supply or increase the cost of renewable energy sources that directly convert solar energy or wind to electricity or heating (Smith and Tirpak, 1989; Nishinomiya et al., 1989).

- Operating characteristics of energy technologies may be modified, changing the cooling and thermal efficiency of units and affecting the operating margin of transmission and distribution systems (Nishinomiya et al., 1989).

- Warming in the Arctic may require some changes in pipeline design to address potential affects of thawing in the permafrost, according to a 1988 study conducted for Esso Canada. Substantially improved slope protection along rights-of-way over permafrost may be required to prevent thawing, which leads to slumping, breaks and leaks (Brown, 1989). A longer ice-free season in the Arctic may facilitate shipping to oil and gas drilling facilities (Lonergan, 1989) and less severe cold weather conditions might result in lower costs for exploration and drilling.

- Heating requirements may be substantially reduced, with the extent of reduction increasing at higher latitudes.

- Climate change may lead to redistribution of populations, resulting in increased investment to supply the needed shifts in energy supply and distribution infrastructure.

- Biomass energy (eg fuelwood for cooking) represents a large fraction of total energy use in some developing countries: more than 80% in most and 90% in some African countries (Tebicke, Remarks, 1989). If biomass production potential is constrained by climate change induced reduction in soil moisture or inundation of arable land, then it will be difficult for nations so affected to replace the energy in view of the capital costs of alternative sources. Biomass for energy may also remove valuable forest cover and it competes with alternative uses of the biomass (eg for building material) or of the land for food production. Biomass currently is used for energy with very low efficiency except for new advanced technologies, such as new cooking-stove designs.

- Increases in storm activity (eg hurricanes, tornadoes, hail storms etc) tend to disrupt energy exploration (eg offshore drilling), production and transportation. This increases the cost and might be constraining on development of some economically marginal resources.

- For some temperate climate areas of the USSR, it has been estimated that increased humidity associated with a global warming of 3°C could result in increased costs of coal-produced electricity because of additional expenses incurred in mining and transporting coal and removing moisture before combustion. This could amount to as much as 6% of operating costs (Vladimirova, 1990).

3.3 Determination of sensitivities

Many of the potential impacts on energy supply, generation and distribution depend on the rates of change and on direction and magnitude of change of specific climate parameters in a region. Different rates of change are likely to result in substantial differences in costs to take mitigative actions, depending on whether normal planning and replacement of facilities can occur or whether the lifetime of existing energy units is reduced. Some locales may experience increased supply of water from climate change without offsetting evaporation; this can reduce costs in differences among technology choices because of availability of water or, in other locales, it can increase costs at existing facilities because of changes in levels of water bodies potentially increasing flooding or changing thermal discharge patterns. Seasonal changes in weather patterns, water supply and insolation may be beneficial or constraining. (Smith and Tirpak, 1989; ICF Inc., 1987.) Thus, the sensitivity of energy activities to climate change can vary greatly with local conditions such as hydrology and water use.

It should also be noted that the effects of policy responses to global warming have not been considered here. Since fossil-fuel energy production and utilisation is a major contributor to GHG emissions, it is likely that any response policy will greatly constrain or increase the price of fuels and electricity produced for fossil fuels. Response strategies may also directly produce shifts in fuels or energy technologies.

3.4 Tasks for the near future

Studies of impacts on energy supply and demand are presently limited in terms of types of potential impacts studied, regions studied and consideration of the range of potential impact under the uncertain and highly variable results of regional climate change provided by GCMs. The rates of change and patterns of change for regions over several decades need to be more properly represented in the impacts assessment. Since new energy sources and technologies are evolving, detailed studies of their capabilities and vulnerability to climate change are needed. In the case of hydroelectric power, possible changes in runoff and demands for water vary greatly with local conditions. Hence, detailed study of each basin will be required to identify the range of possible climate change impacts.

Studies are needed of potential effects of climate change on availability of biomass energy, especially in developing countries. Future conditions need to be considered, including population and competition for biomass and land resources, along with possibilities for improvements in efficiency or substitution for utilisation of biomass energy.

A survey of the availability of non-traditional forms of energy such as wind or solar power would be helpful. This survey could develop an atlas of availability of such resources in countries around the world together with a preliminary analysis of how changed weather circulation patterns and cloud cover might affect their potential for energy production.

There is a general need to examine energy sector impacts in depth on an integrated fuel-cycle basis, including all key stages from exploration through consumption and disposal of waste, in order to capture the cumulative impact of many small effects and to assist decision making among alternatives.

The potential indirect impacts on energy use patterns due to policy responses to global warming should be analysed, including secondary effects on the natural environment and on regional economies.

4 Summary of likely impacts of climate change on transport

The study here is directed at the impacts of climate change on services and facilities for the transportation of goods or persons.

4.1 Scope and limitations of the assessment

Analysis of the effects of climate change is made according to two interrelated systems: infrastructure and traffic on the one hand, and by transportation means, defined as airways, waterways, roads and railways, on the other hand.

The studies concerning the likely implications of climate change for transport are quite restricted in geographic scope, being limited largely to three countries: Canada, the UK and the US. It is uncertain how these studies in three high latitude Northern Hemisphere nations are representative of likely transport impacts on the globe as a whole.

4.1.1 Direct impacts of climate change

Climate change is likely to have a number of direct effects on transportation. Increased temperature can be expected to reduce sea and river ice and snowfall, affecting shipping, air travel, highway and rail transport. Increased sea-levels associated with global warming could be expected to affect transport infrastructure such as ocean ports. Changed hydrologic and evapotranspiration patterns associated with climate warming are likely to shift water levels on lakes and rivers, affecting navigation on inland waterways. Changes in frequency and seasonality of storms may affect airways, waterways, roads and railways.

4.1.2 Indirect impacts of climate change

Some elements of transport are likely to be significantly affected by public policies or consumer actions designed to restrain emissions of GHG. This is particularly true of the automotive industry. A rise of several degrees Celsius in mean global temperature would require only minor adaptations in engine design because of the wide tolerances already built into cars; yet public concern about GHG emissions may lead to more stringent fuel economy standards, taxes on carbon-based fuels, consumer movement to smaller or more fuel-efficient vehicles, public policies or consumer shifts favouring alternative fuels in place of gasoline, and shifts toward greater reliance on mass transit.

4.1.3 Potential impacts on the transport sector of governmental regulations seeking to curtail emissions of greenhouse gases

Concern over global warming has added a new factor to transport and energy policy debates, affecting a recent government decision in the US to set the Corporate Average Fuel Economy (CAFE) standard at 27.5 miles per gallon rather than moving it to 26 mpg as sought by some industry petitioners. Although assessments of the likely impacts of such potential regulatory policies is conjectural, concern over global warming would seem likely to result in regulatory or tax measures encouraging fuel efficiency, more stringent emission controls on automobiles, and greater support for mass transit.

4.1.4 Potential impacts on transport sector of shifts in consumer patterns in order to curtail emissions of greenhouse gases

Public concern over GHG emissions may cause consumers to purchase more fuel-efficient cars, move to non-carbon or lower carbon content fuels, and even abandon private car travel for mass transit. It appears too early to detect any pronounced shift in consumer preferences in response to concerns about greenhouse emissions. Yet environmental groups are already promoting product or fuel shifts as a result of concern over GHG.

4.2 Assessment of impacts

Studies of the likely impact of climate change on transport have centred almost entirely on three Northern Hemisphere nations: Canada, the UK and the US. A large portion of the North American impact analysis has centred on the Great Lakes region where inland waterways are significant to both the Canadian and US economy.

In an effort to compare relative impacts of climatic variables in the UK transportation modes, Parry and Read produced the following table (Table 5.3).

4.2.1 Impact of climate change on airways

Aircraft today are engineered with strong tolerances for widely varying climatic conditions. They may fly in temperatures as low as -65°C and in winds as great as 400 knots (Parry and Read, 1988.) Most major airports have provisions for snow and ice

Table 5.3 Average number of events per annum in which major climatic variables affect UK transport system

Variable	Low cloud	Snow	Rain	Ice	Fog	Wind
Transport system						
Rail	na	3	1 (landslide)	30	2-3	na
Road	na	9	10	40	2-3	2
Air	20	5	0.5	20	20	5
Sea	na	na	na	2	20	30-40
na = not affected						

Source: Parry and Read (1988).

control, but fog and low cloud remain serious problems, although technological improvements may be minimising these visibility problems at major airports. Climate warming would be likely to reduce snow or ice problems which hinder air travel. It is unclear what its effects would be on fog and low clouds.

Air temperature is a critical factor in aircraft performance during take off, especially from aircraft situated in warmer regions and at higher altitudes. Already under some conditions of high temperature and low barometric pressure, aircraft either have to take off with reduced loads or delay taking off until the temperature drops. Helicopter operation is also affected by high temperatures. Temperature rise due to greenhouse warming may exacerbate such problems.

If global warming results in a change in prevailing winds, the orientation of runways may need to be changed for safety and efficiency considerations. Such changes in runway orientation may not be feasible in existing airports because of local geographic constraints and environmental considerations, such as noise impact on urban areas under the new potential flight paths.

Some major airports are located near the ocean and may be vulnerable to sea-level rise. An Urban Institute study projected that a 1 m sea-level rise would necessitate roughly $30 million in drainage improvements for Miami International Airport, Florida, US, (Miller, 1989).

4.2.2 Impact of climate change on waterways

Climate change is likely to produce very different effects on shipping on inland waterways as opposed to maritime traffic on the oceans or seas. Changes in hydrological and evaporation patterns could be expected to change levels of some inland waterways, sometimes causing lake levels to drop. Global warming would, however, produce a rise of perhaps as much as a metre in sea-levels worldwide. The relative sea-level rise would vary modestly on particular coasts due to local subsidence and crustal rebound.

4.2.2.1 Impact of climate change on inland waterways

Virtually all of the analysis of likely impacts of climate change on inland waterways concerns potential effects on the Great Lakes of Canada and the US. An effective CO_2 doubling may result in significantly lower lake levels throughout the five Great Lakes: Superior, Huron, Michigan, Erie and Ontario (Sanderson, 1987; Quinn, 1988; Bolhofer, 1989; Smith, 1989). These lake levels have varied significantly in the past with quite low lake levels experienced in the 1964-65 period. Changnon et al. (1989) have studied the effects of these conditions on Lake Michigan, Chicago and the Illinois shoreline. They report significant increases in dredging cost for Calumet Harbor and Waukegan Harbor in 1965, and inflow of water into the Chicago River and the canal diversion system. This system uses water from Lake Michigan in order to maintain sufficient flow and water levels in the Illinois River system to meet barge transportation and sanitation needs. The study projects that payloads on lake carriers were

Table 5.4 Estimated economic impacts of lowerings of the levels of Lake Michigan over a 50-year period (1990-2040)

(Costs in millions of 1988 dollars needed to address future lake levels at indicated depths below average level of Lake Michigan, 1950-80)

	1.25 m lower	2.52 m lower
1. *Recreational harbours*		
Dredging	30 to 50	75 to 100
Sheeting	15	35
Slips/docks	20*	40*
2. *Commercial harbours*		
Dredging	108	212
Sheeting/bulkheads	38	38
Slips/docks	40*	90*
3. *Water supply sources*		
Extending urban intakes	15	22
Wilmette Harbour intake	1	2
4. *Beaches*		
Facility relocations	1-2	1.2
5. *Outfalls for stormwater*		
Extensions and modifications	2	4
Totals	**$270 to $291 million***	**$519 to $545 million***

* Some costs could be partly covered by normal replacement expenditures over the 50-year period.

Source: Changnon et al. (1983) p25.

reduced between 5% and 10% resulting in higher shipping costs.

Changnon et al. report some impacts on recreational boating. Shallow water caused some problems for pleasure crafts in harbours and inlets to harbours. Additional dredging was required in some private and local urban inlets and small-craft harbours, including Montrose, Belmont, and Jackson Harbours of the Chicago Park District. Some docks were extended and others lowered and ladders were constructed to get from existing docks to boat level.

In projecting potential impacts of future lower lake levels on Lake Michigan, Changnon et al. make projections of overall costs for a lowering of lake levels of 1.25 m and 2.52 m between 1990 and 2040. (See Table 5.4).

Many harbours have wooden slips and docks and exposure over time of the below-water portion of these structures would produce dry rot. A 1.25 or 2.52 m decrease in lake levels would necessitate replacement of all wooden slips and docks. Much of this, however, would be handled as part of normal replacement costs. All pleasure boat harbours could be adjusted through dredging to handle a 1.25 m reduction, but a 2.52 m lowering of lake levels would make some harbours unusable. Dredging costs for the 1.25 m reduction were estimated at $3 to $5 million per harbour and for a 2.52 m lowering at $5 to $10 million per harbour.

Using a GISS 1984 climate scenario indicating that mean Great Lakes lake levels may be reduced 30-80 cm, Sanderson (1987) calculates that average annual costs to Canadian Great Lakes shipping companies for the four principal cargoes, iron ore, grain, coal and limestone, may increase approximately 30% and that in nine years out of ten, shipping costs are likely to equal or exceed those of the low lake levels of 1963-65.

Another major change reported by Sanderson is that maximum ice cover on the Lakes may decline from 72% to 0% for Lake Superior, 38% to 0% for Lake Michigan, 65% to 0% for Lake Huron, 90% to 50% for Lake Erie, and 33% to 0% for Lake Ontario, thus permitting an 11-month ice-free shipping season.

Climate warming might be expected to result in substantial cost savings for transport of goods in the Mackenzie River region of Canada's Northwest

Territory, where over 90% of all goods are shipped by barges. Extension of the barge season from its present four months (mid June to mid October) by about six to eight additional weeks would be expected to result in decreased costs (Lonergan 1989).

4.2.2.2 Impact of climate change on ocean shipping

There is little data or analysis concerning the potential impacts of climate change and associated sea-level rise on ocean shipping and on sea ports. An extensive study of the physical and ecological impacts of climate change on the marine environment of Atlantic Canada (Stokoe, 1988) does provide an excellent summary for the provinces of Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland.

Some benefits are reported from the reduction of sea ice. Absence of sea ice south of Labrador in most years could eliminate Coast Guard ice-breaking requirements, which now cost $15-$20 million Canadian each year. Absence of sea ice could cut costs for ferry services and marine transport and permit extended seasons for some routes. These gains for Atlantic Canada might be offset in part by loss of winter marine traffic to Churchill, Montreal and Saint Lawrence Seaway ports as these ports become ice free or accessible nearly all year round.

Negative aspects of climate change for Atlantic Canada include damage to infrastructure resulting from sea-level rise. Stokoe projects losses of several hundred million dollars (Canadian) for each of the following categories: (i) urban waterfront land, (ii) buildings, (ii) breakwaters, (iv) bridges and causeways, (v) roads and railways, (vi) fish processing plants and (vii) wharves.

4.2.3 Impact of climate change on roads

The only comprehensive study of likely impacts of climate change on roads of a large region is that contained in Stokoe's study of Atlantic Canada. Costs in the range of hundreds of millions of dollars are ascribed to each of the following categories: (i) bridges and causeways and (ii) roads and railways.

An Urban Institute analysis of the effect of a 1 m sea-level rise on Greater Miami, Florida, US, (Miller, 1989) found that this 'would require raising most bridges to ensure adequate under-clearances, to prevent erosion beneath abutments, lifting of steel and box culverts, and pavement failure in bridge approaches, and to reduce vulnerability to storm surges during hurricanes.'

The same study found beneficial effects on road costs from climate warming in Cleveland, Ohio, US, where climate change could cause annual snowfall to drop from 50 to roughly 8 inches, reducing annual snow and ice control costs by about $US4.5 million and producing a savings of about $700,000 each year from decreased frost damage to roads and bridges. (Miller, 1989.) A decrease in deep freezes and freeze-thaw cycles would result in fewer potholes, while warmer temperatures and improved drainage resulting from higher evaporation rates could allow use of thinner pavements in many areas, but require enhanced expansion capabilities. (Hyman, et al., 1989.) The savings in Cleveland, Ohio, are projected at about 1% of road reconstruction costs, and 3% of resurfacing costs (Hyman et al., 1989).

Parry and Read (1988) in their study of impact of climate variables on transport in the UK state:

> Although the U.K. has a comparatively mild and equable climate, the extremes of weather or climate are not always the most costly or dangerous, and weather thresholds of economic or safety interest can be in the midst of a range. To illustrate, a temperature of 0°C, though hardly extreme is critical because ice is most slippery when its temperature is at zero. Thus although the U.K. winter climate is warmer than that of most of continental Europe, because it is less predictable as far as the 0°C threshold is concerned, icy roads are potentially more dangerous in the U.K. and more difficult to manage.

This observation suggests reason for caution in predicting likely effects of global warming on highway safety.

Although the Mackenzie River region of Canada might be expected to realise some cost savings owing to a longer ice-free season, allowing barge traffic, some of these savings might be offset by a decrease in the winter road operating season as ice bridges may be usable for only a limited period (Lonergan, 1989). It appears possible that this problem could be a concern in other regions of the Arctic.

The greatest impacts on the automotive sector are likely to result from response strategies to global warming and related air pollution. Walsh (personal communication, 1989) points out that increased global warming will increase photochemical activity and increase tropospheric ozone for a given emission of hydrocarbons and nitrogen oxides (NO_x). Thus, it will increase pressure for greater control of these emissions from motor vehicles. Since tropospheric ozone is a GHG, global warming provides another impetus for controlling NO_x from vehicles. This should in turn encourage more stringent emissions control using existing conventional technology but, increased concern about $C0_2$, is likely to increase the pressure for advanced fuels and technologies such as fuel cells, hydrogen, solar etc (Walsh, personal communication, 1989).

Pressures are also likely to develop for stringent controls on emissions of carbon monoxide because of its large potential to enhance the Greenhouse Effect. Global CO levels are increasing 0.8% to 1.4% per year according to Khalil and Rasmussen (1988). Carbon monoxide, although a radiatively inactive gas can, through its interaction with OH, serve to increase the concentration of several important GHG (Ramanathan, 1988). Dr Gordon MacDonald (1989), in testimony before the US Senate Committee on Environment and Public Works stated:

> Carbon monoxide could thus be indirectly responsible for increasing greenhouse warming by 20 to 40% through raising the levels of methane and ozone... . Carbon monoxide participates in the formation of ozone and also in the destruction of hydroxyl radicals, which are principal sinks for ozone and methane GHG. Because carbon monoxide reacts rapidly with hydroxyl, increases levels of carbon monoxide will lead to higher regional concentrations of ozone and methane. Measures to reduce carbon dioxide emissions will assisting in controlling global warming.

The combined concern over the aggravation of air pollution as a result of global warming and over the contribution of auto emissions to the build-up of concentrations of GHG seems likely to push governments to enact increasingly stringent auto emissions controls and perhaps to encourage new fuel technologies.

4.2.4 Impact of climate change on railways

Relatively little data exist concerning potential impacts of climate change on railways. Miller (1989) reports that 100 °F weather expanded railroad tracks in the US in the summer of 1988, forcing Amtrak, the major US passenger railway, to reduce speeds from 125 to 80 miles per hour between Washington and Philadelphia, and allegedly caused a train wreck that injured 160 people on a Chicago to Seattle route. Global warming could be expected to exacerbate such heat-stress-related problems for railways, while producing some offsetting benefits through reduced snow obstruction of tracks. No systematic analysis exists in the literature, however, on the likely aggregate impacts on railways of increased heat stress or reduced snowfall.

4.3 Determination of sensitivities

The studies in the literature concerning likely impacts of climate change on transport largely concern three high-latitude Northern Hemisphere countries, Canada, the UK and the US. It is not clear how much one can generalise from these effects to likely effects in the Southern Hemisphere or in tropical and subtropical regions of the Northern Hemisphere. Shipping in such regions may be affected greatly by changes in tropical cyclone patterns. Such changes could have potentially large consequences in places such as Australia (Henderson-Sellers and Blong, 1989; Pearman, 1988).

No analysis exists in the literature of the likely overall impact of greenhouse response strategies on the transport sector. It is likely, however, that the transport sector, especially the automotive sector, will become a major focus of greenhouse policy concern. Tracing CO_2 trends in Canada, Jessup (1989) states that in 1985, Canadian cars, trucks and other vehicles produced 34.5 mt of carbon, approximately 30% of Canada's total emissions of 118 mt. This motor vehicle component was, Jessup points out, the largest single component of Canada's carbon emissions, greater even than the 25.4 mt produced by electricity generation. Jessup goes on to suggest that governmental regulatory and taxing policies should be fashioned to reduce $C0_2$ emissions. Yet no analysis exists in the literature of how such policies might produce shifts between various transport modes. Although it is possible, even probable, that aggressive governmental policies to restrain greenhouse emissions would produce shifts between various transport modes, the absence of some systematic analysis makes such projections quite conjectural.

4.4 Tasks for the near future

Research and analysis of the following are needed:

- implications of changes in tropical storm patterns, sea-ice extent, and iceberg flow on ocean shipping;
- likely impacts of government regulatory policies to restrain greenhouse emissions on the automotive sector, including improvement of efficiency in transportation facilities, likelihood of fuel switching, increased use of mass transit, or shift to other modes of transport;

- changes in water levels in inland waterways and potential effects on inland shipping;
- likely impacts on transportation infrastructure in tropical areas of climate warming and sea-level rise;
- likely impacts on transport and roads of a thawing of the permafrost associated with warming in the arctic and other cold regions;
- the impact of likely climate-induced population migration on traffic and transport patterns;
- transportation models, permitting projection of likely shifts between transportation modes as a result of climate change.

5 Summary of likely impacts of climate change on industry

The term 'industry' here applies specifically to the production of goods and services. Thus, the impacts assessed in this section are primarily the direct effects of climate change on the producing of goods and services and the related production facilities. The energy industry and the transport industry are separately covered in the two preceding sections.

5.1 Scope and limitations of the assessment

The change in climate that is predicted to accompany the rise of levels of CO_2 and other infrared-absorbing gases in the atmosphere, a so-called greenhouse effect-induced global warming, is expected to have far-reaching consequences on the world's industries. Each aspect of the 'greenhouse' scenario will contribute individual as well as aggregate impacts to the worldwide industrial community. Additionally, the effects can be broken down into direct and indirect aspects.

5.1.1 Direct impacts of climate change

The direct impacts of climate change are likely to vary considerably between different industrial sectors. One effort to assess impacts of climatic variability across industrial sectors of an entire nation is an unpublished (1985) British Meteorological Office Study cited by Parry and Read, (1988), at p2. This study shows the sensitivity of various industrial sectors within the UK to climatic variability by comparing the interannual variation in value of turnover in each sector due to weather with the total value of turnover in that sector. The most weather-sensitive industries in descending order as a ratio of interannual variability to total value of turnover were agriculture (30.1%), transportation and communications (20.2%), construction (14.7%), energy (9.9%), consumer manufacturing (6.9%), retail and distribution (5.9%), other services, including television (4.3%), minerals and metal manufacturing (3.0%), engineering (2.9%) and professional services (2.0%).

Generally, the more weather-sensitive industries on a historical basis would appear more vulnerable in a rapidly warming world; nevertheless, some historic losses may become less of a factor, eg disruption due to blizzards or ice storms. It is possible that warming will have quite differential impacts on particular industries, in some cases reducing variability and in other cases magnifying it.

5.1.2 Indirect impacts of climate change

Among the most significant likely impacts of climate change on the industrial sector are public policies designed to restrain emissions of GHG. Such policies could enhance opportunities for energy-efficient industries and industries that produce or use low quantities of GHG while penalising industries that produce large quantities of GHG. Among the greatest potential impacts on the manufacturing sector may be requirements to increase the efficiency of manufacturing processes to reduce energy consumption and GHG emissions. Among those industries that may be especially affected by response strategies is the Portland cement industry, which generates, according to one estimate, about 1181 million tons of global CO_2 emissions each year (Margolin, 1990). At this time, there is little analysis to project these potential impacts of response strategies on industry.

5.2 Assessment of impacts

There are relatively few detailed studies concerning the likely impact of climate change on industry, and these studies have been performed in only a few countries: principally Australia, Canada, Japan, the UK and the US. The most significant of these studies are reviewed by industry grouping.

5.2.1 Direct impact of climate change on particular industries

Virtually all of the studies concerning impacts of climate change on industry involve direct impacts such as changes in temperature, seasonality and frequency of precipitation, storm patterns, sea-level rise or water flow. These changes can be divided into a number of categories as follows:

5.2.1.1 Weather-dependent demand

The most detailed studies of changes in demand due to climate warming have been done by Linder and Gibbs (1988), Parry and Read (1988) and Linder (1989) concerning energy demand. These are discussed in the chapter on energy above.

Climate warming could be expected to increase demand for such cold drinks as carbonated beverages, fruit juices, lemonade and ice tea, and to reduce demand for such hot beverages as hot coffee or hot tea. No reliable projections of the likely magnitude of such changes in average consumption are available. Global warming might also be expected to affect consumer demands for certain foods, but no studies are available to project such potential effects.

The clothing industry would also be likely to experience changes in consumer demand owing to global warming. There would appear reason to expect increased demand for cotton clothing and certain synthetics that are comfortable in hot weather and to expect some potential reduction in demand for wools. In addition, the design of clothing could be expected to change to greater use of lightweight materials and use of short-sleeve shirts or blouses. Climate warming will affect the beverage, food and garment industries and other sectors. Effects will probably stimulate demand for some products and reduce demand for others. There appear, however, no systematic projections of such likely effects. One of the few studies of weather-dependent demand concerns wide fluctuations in sales of air-conditioners. In Japan on days over 35°C air-conditioning sales tend to rise by 40,000 units (Sakai, 1988).

5.2.1.2 Weather vulnerable industry

Some industries appear especially sensitive to weather conditions, with extreme cold and, to a lesser extent, extreme heat appearing to limit production in the construction industry and severe storms being a considerable detriment to such industries as offshore oil and gas drilling.

In surveying impacts of climatic variability on UK industry, Parry and Read report that rainfall is responsible for more delays than any other climatic variable and that snow will affect operations on construction sites as well as transport to the sites. In the UK, they report:

> Snow depth in December and January, and mean monthly temperatures in November and December seem to be the most important climatic variables determining productivity in the construction industry, but sometimes with a lag effect so that, for example, the size of the construction labour force in February is related to air temperature two or even three months earlier (at p. 30).

The analysis by Friedman (1989) on insurance implications for the US of climate change, provides a potential projection of changed vulnerability of storm-sensitive industries. Friedman projects that an increase in seasonal sea surface temperature of only 0.5°C could be expected to lengthen the hurricane season by 20 days and that it could increase the annual average loss expectancy due to hurricane-caused catastrophes by 40%. Such changes presumably would increase storm vulnerability of such industries as coastal fisheries and offshore oil and gas drilling.

In some high-latitude areas outside of traditional hurricane or tropical cyclone belts, reduced sea ice and icebergs could yield major benefits for offshore oil and gas drilling. Sea ice and icebergs currently have major adverse impacts on such exploration and development on the Northern Grand Banks and Labrador Shelf of Canada. During the extremely severe ice year of 1984-85, 8952 hours of drilling downtime resulted from ice problems and produced losses of $40 million (Canadian), based on a cost of $100,000 per 24-hour day (CCD 88-07).
In the event that global warming causes an increase in the intensity or frequency of tropical cyclones, this could result in lost industrial productivity as industry in the affected regions is forced to suspend operations during the storm threat and its aftermath.

5.2.1.3 Climate-utilising industry

Some industries are directly dependent on climate for their success. The skiing industry requires sufficiently low temperatures for snow (or at least artificial snow), and some other recreational industries such as water sports or swimming pool sales may benefit from warmer climates.

In a study of implications of an effective CO_2 doubling for tourism and recreation in Ontario, Canada, Wall (1988) projects that the downhill ski season in the South Georgian Bay Region could be eliminated with an annual loss of $36.55 million (Canadian) per annum in skier spending there and a $12.8 million drop in spending at Collingwood. Some of these losses would be offset by extended seasons for summer recreational activities. In an analysis of likely implications of an effective CO_2 doubling for downhill skiing in Quebec, Lamothe and Periard (1988) project a decrease in the number of skiable days of 50% to 70% for Southern Quebec and that ski resorts equipped with snow-making devices would probably experience a 40% to 50% reduction in the number of skiable days. The study projects sizeable losses to the Quebec economy. In a study of skiing in Japan, Aoki (1989) finds skiing highly sensitive to snowfall.

The wine-producing industry is especially sensitive to climate. Tom Roper, Minister for Planning and Environment of Australia's second most populous state, Victoria, recently projected,

> The increased temperatures would be likely to severely affect the variability of current temperate fruit production ... . Victorian wine growers could see their cool climate vineyards disappear and growing conditions transformed over the space of 30 years. (Roper, 1989).

5.2.1.4 Local resource-dependent industry

Some industries are very dependent on the availability of local resources which may be affected greatly by changes in climate. Climate-induced changes in the availability, or cost of obtaining crops, domestic animals, fish or aquatic animals, wood, water, or mineral resources could affect the standing of such industries as the agricultural processing industry, the forest and paper products industry, the fish-processing industry, the hydroelectric power industry, and such energy-dependent industries as the aluminium manufacturing industry.

There is a large number of studies of the likely impact of climatic change and of climatic variability on agriculture. Perhaps the most comprehensive work is Parry et al., (1987). A number of competing factors may affect the cost, quality and availability of agricultural raw materials. Increased concentrations of CO_2 in the atmosphere are expected to enhance the rate of photosynthesis and increase the rate of growth of most plants, but this change is expected to vary greatly among plants. Other climate-change-related variables which may have mixed or negative results include changes in length of growing season, frequency and seasonality of precipitation, rate of évapotranspiration, heat stress and changes in UV-B radiation.

For agricultural industries dependent on a single agricultural raw material, eg fruit or wine production, wool or fibre industry, changed local availability of such materials might affect the competitive standing of such industries. Reliable projections of such effects do not, however, seem available at present.

Climate change is expected to have significant effects on forest productivity (Shands and Hoffman, 1986; Winget, 1988; Regens et al., 1989). These effects could ultimately affect the competitive position of the timber and logging industries, pulp and paper products industries and the wood products industry.

Regens et al. foresee major shifts in US forest markets ultimately affecting the forest products industry, possibly causing a shift northward of the industry's processing infrastructure. Yet such a shift would be constrained, they maintain, by a huge entry cost for new paper mills (about $US500 million, each in current dollar terms) and the lack of adequate water supplies and transportation routes servicing alternate potential mill sites. Opening of new sawmills where the investment runs only $US10 million to $US20 million would be accomplished much more readily.

Summarising results of a Symposium on Implications of Climate Change for Commercial and Sport Fisheries in North America, Topping and Bond (1988) conclude that fish productivity is likely to rise with an increase in mean water temperature; so a moderate global warming might be expected to increase fish yields. Distribution and range of particular fish species may change significantly as a result of an increase in water temperature. In some cases, secondary environmental effects associated with climate warming such as greater estuarine salinity might offset or overwhelm the direct benefits from warmer water temperatures. Topping and Bond project that the greatest threat to global fisheries productivity from climate change may stem from increased UV-B radiation resulting from a depletion of the stratospheric ozone layer.

Tsyban et al. (1985), however, identify two possible adverse impacts associated with global warming which could each act to reduce significantly world fisheries production. These include a potential reduction in the intensity and areas of oceanic upwelling and a corresponding loss of nutrients, and a decrease of the pH in water calculated at about 0.3 for a CO_2 doubling, which may harm marine organisms. See Chapter 6 for an extended discussion of these issue.

Although the effects of climate warming may be of benefit to fresh water fisheries such as those in the US-Canadian Great Lakes region (Regier et al., 1988), such associated effects as sea-level rise could pose major problems for the fish-processing industry in coastal areas. Stokoe (1988) notes that fish-processing facilities in Canada's Atlantic provinces have a capital value of $1 billion dollars (Canadian), and most are situated at or near the water's edge and could be vulnerable to inundation or damage as a result of sea-level rise.

Studies of likely impacts of climate change on aquaculture are sparse, with Rothlisberg et al. (1988) indicating that climate warming could lead to an increase in banana prawn catches and a decrease in tiger prawn catches in the Gulf of Carpentaria off Australia. Kennedy (1989) concludes, after a study of likely impacts of climate change on aquaculture in the Chesapeake Bay region of the US, that soft clams and winter flounder may disappear from the bay under a climate warming of 3°-4°C.

5.2.1.5 Site-dependent industry

Climate change and sea-level rise may have significant and mixed impacts on such site-dependent industries as the tourism and resort industry, such transportation industries as highways and mass transit, and a whole range of coastal industries, particularly the beach and recreation industry.

A preliminary Japanese case study projects that in the absence of concerted human efforts to build coastal defence, sea-level rise of 1 m could inundate the port area of 1900 km^2 and cause damage to nine million Japanese (Ministry of Transport of Japan, 1989). An even greater proportion of industry may be vulnerable in Africa, where industry tends to be concentrated in capital cities, a large portion of which are seaports (Tebicke, 1989).

The impacts of sea-level rise on beaches and coastal resorts may be quite great. Even a rise of a fraction of a metre could produce wide-scale erosion on vulnerable coasts, particularly those with very gradual slopes such as much of the US Atlantic and Gulf Coasts. The cost of beach nourishment, ie dredging sand from the ocean to rebuild major recreational beaches, may be quite considerable. Leatherman (1989) estimates that the costs of such an engineering approach to protect major US recreational beaches would be likely to range from $US2.3 billion to $US5.9 billion by the year 2020.

A major uncertainty affecting the recreational industry is how these costs will be apportioned by coastal nations facing such problems. If these costs are borne largely by the national government, as they have generally been to date in the US, the added cost to coastal recreation and related industries may be modest. If local governments in coastal areas are made to face the primary burden of financing such projects, this is likely to result in more beach abandonment and greater tax burdens upon coastal industries and communities when such projects are carried out.

5.2.1.6 Variability-dependent industry

The principal impact of weather or climate on some industries involves the occurrence of extreme events which cause potentially large losses. Perhaps the most significant of these industries is the insurance industry which will insure against risk to property, risks of death or injury, medical expenses and damage to crops. A second complex of industries likely to be affected by climate change includes those that are related to the construction or maintenance of infrastructure, dams, bridges, causeways, highways and other long-lived investments that must be built to stand up to ordinary wear and tear as well as extreme events such as floods, hurricanes, blizzards and ice storms.

The most detailed analysis of likely implications of climate change for the insurance industry is a Friedman (1989) analysis of insurance pay outs on weather related catastrophes in the US. In the following table he presents an analysis of likely annual losses to US insurers from weather related catastrophes under current climatic conditions.

Friedman calculates that these weather-related insurance losses are likely to rise about $300 million on an annual basis in a typical year during the transition period between 1990 and 2010 during which a greenhouse warming would occur. Although some modest gains would be realised by a reduction in winter storm damage, this would be overwhelmed by sizeable increases in hurricane damage and modest increases in damage from severe local storms. Friedman, Table 5.6, lists the resultant increases in damage.

Parry and Read (1988) report that weather-related insurance claim pay outs in a normal year represent about 40% of the UK's annual total of about 2000 million pounds. The greatest problems for the insurance industry in the UK have been associated with wind storms, severe cold and coastal flooding incident to storm surge.

Peele (1988) projects that insurance claims in Australia from losses associated with tropical cyclones, hailstorms, floods and brushfires associated with greenhouse warming will result in increased premiums on property insurance and a movement to higher deductibles.

Berz (1988) in an analysis of likely impact of climate change on international reinsurance projects that costs are likely to increase greatly as the increased intensity of convective processes in the atmosphere raises the frequency and severity of tropical cyclones, tornadoes, hailstorms and storm surges in many

Table 5.5 Estimated total 1989 damages by storm type*

Present climatic regime

Storm type	Number of catastrophes	Percentage	Total damage production (billions of dollars)	Percentage	Average annual damage production
Hurricane	51	6.4	$27.2	40.2	$680,000,000
Severe local storm	649	81.2	31.4	46.4	$780,000,000
Winter storm	99	12.4	9.1	13.4	$230,000,000
Total	799	100.0	$67.7	100.0	$1,690,000,000

* Damages resulting from a repeat of each of the catastrophe-coded weather events that have occurred in the past forty years and which would cause at least $5 million in damage to presently insured properties in the US

Source: Friedman, D.G. (1989 p390).

Table 5.6 Estimated change in the annual damage producing potential of wind and hail*

* Includes insurance industry coded catastrophes caused by the insured perils of wind and hail between the present climatic regime and an undefined time during the transitional climate period (1990-2010) when a projected warming due to the Greenhouse Effect might be attained. Damage potential is expressed in 1989 dollars.

Storm type	Annual damage based on present climatic conditions	Annual damage based on change in annual damage potential	Transitional climate condition
Winter storm	$ 230,000,000	-$ 20,000,000	$ 210,000,000
Hurricane	680,000,000	+ 270,000,000	950,000,000
Severe local storm	780,000,000	+ 25,000,000	850,000,000
	$1,690,000,000	$275,000,000	$1,965,000,000

Source: Friedman, D.G. (1989 p393).

parts of the world. In certain coastal areas he predicts that insurance coverage will be available only after significant restrictions have been applied such as high deductibles and low liability or loss limits.

Stark (1988) argues that the Greenhouse Effect will affect coastal and marine structures and developments in three principal ways thus requiring engineers to build into the design of these structures and projects a rise in mean sea levels, or potential increase in frequency of and areas affected by tropical cyclones and an increase in intensity of cyclones. Current designs are not adequate, Stark maintains, to withstand storm surges and wave attacks that can be anticipated under existing climate change scenarios.

Flynn et al. (1984) assessing the implications of sea-level rise for hazardous waste sites in coastal floodplains conclude that serious health and environmental problems may arise from the flooding of some active US hazardous waste facilities even in the absence of sea level rise. Sea-level rise concerns may, they suggest, require relocation of some existing hazardous waste facilities and strengthened design criteria for new sites. The hazardous waste industry is likely to be directly affected by concerns about flooding from storm surge.

5.2.2 Indirect impacts of climate change on industry

An analysis of likely indirect impacts of climate change on industry is speculative given the paucity of reliable studies on direct impacts. Climate change appears likely to alter consumer demand in ways not yet perceived. Travel and transportation patterns are likely to change affecting such industries as tourism. Shifts in natural resources availability resulting from climate change will change international trade relations, affecting investment in seemingly unrelated industries.

Among the more predictable of the indirect effects is the creation of market opportunities for industries that seize the opening created by public concern about the greenhouse effect. These may include manufacturers and marketers of energy conservation devices, coastal engineers, developers of water conserving or desalinisation technologies, agricultural researchers or biotechnology firms that develop drought resistant or temperature resistant crops.

The converse of this effect may be increased regulatory pressures or tax burdens on firms that produce substantial quantities of GHG emissions.

5.3 Determination of sensitivities

The principal limitation in any review of climate impacts on industry is the inability of current climate models to give reasonable projections of regional and local climate scenarios. This is particularly true concerning water availability, a crucial variable in projections of impacts on many industries.

In addition, analyses of climate impacts on industry exist in only a few countries, all in the industrialised world. There is strong evidence to suggest that developing countries will bear a major part of the burden of rapid and large-scale climate change, and it is likely that industry in these countries, particularly that sited in coastal areas, will be profoundly affected (Tebicke, personal communication, 1989).

5.4 Tasks for the near future

More case studies of likely impacts on particular industries are needed. Many of these studies should be directed at developing country industries. Central to this analysis is a projection of the likely change in the production map of primary products as a result of climate change. Changes in the price and availability of primary products will affect the competitive position of industry in developing countries. Such studies could have major implications for development planning and investment policies. Analysis should also be performed of market opportunities created by the new global focus on and response to greenhouse warming.

Mechanisms should be developed for ensuring growth of climate impact expertise within developing countries to cover the whole range of climate impacts. This could be facilitated through the funding of regional climate centres and rotation of scholars from various affected countries to these regional centres.

There is also a strong need to involve industrial strategic planners in order to fine-tune the research and analysis of industry impacts and ensure that the results of such analysis are incorporated in industrial planning.

6 Summary of likely impacts of climate change on human health

This section summarises the likely effects on human health following both global warming and UV-B radiation increase.

6.1 Scope and limitations of the assessment

The study assesses acute, chronic and ecotoxicological effects of global climate change on human health (Figure 5.2).

6.2 Assessment of impacts

Global climate change may lead to change directly in morbidity and mortality through global warming and through UV-B radiation increase. Global climate change is likely to affect the ecosystem and alter the human hazards such as parasites and chemical pollutants and also affect human health by producing changes in air quality and water quality.

6.2.1 General climate effect

Human beings have the potential to adapt to climate change not only by physiological, but also by social and cultural adaptive measures, such as hygiene practices, medicine and agricultural traditions. Owing to these abilities of adaptation, human beings can live throughout the world. Therefore, it is necessary to study the capacity for adaptation to extreme climate.

Among major causes of mortality, cardiovascular disease, cerebrovascular disease, hypertensive heart disease, and cancer, are influenced by a variety of environmental factors including climate, urbanisation, social environment and life styles. In the economically developed countries, these diseases cause over two-thirds of total mortality. The time trends of incidence of death may be related to change of environmental factors, such as life styles and urbanisation.

In temperate and cooler regions, seasonal trends of the mortality of cardiovascular, cerebrovascular, and hypertensive heart diseases indicate a winter maximum and summer minimum (Momiyama and Katayama, 1972). Cancer trends, however, are not seasonal. The seasonal trends of major causes of death have changed. For example, there has been a deseasonalisation of infant mortality in Japan. Global warming may change the environmental factors and affect the time trends and seasonality of these diseases in many countries.

The effect of global climate change on human health may also be detected most sensitively in changes of some seasonally changing biological phenomena. Birth seasonality, one of the most distinct seasonal phenomena in human reproductive physiology, may be affected by global warming (Miura, 1987).

Hypothermia, which is caused by exposure to extreme cold in winter, also shows seasonality. Accidental hypothermia of the aged was often discovered in the morning because of defective heating systems. As a result of global warming, the incidence of accidental hypothermia of the aged may be reduced (Iriki and Tanaka, 1987).

6\2.2 Heat stress

In recent years, cardiovascular mortality has increased in many industrialised and developing countries (United Nations, 1986). Since heat conservation and loss by the human body are primarily controlled by the cardiovascular system, cardiovascular diseases may increase during heat stress (Weihe, 1985).

Heatwaves may be associated with increases in morbidity and mortality (Longstreth, 1989; Schuman, 1972; Marmor, 1978). Threshold temperatures for heat stress are relative rather than absolute. The higher summer threshold temperatures are observed in the hot climate regions while the lower are found in cool climates.

While deaths of infants under the age of one were not examined, the categories which appeared most sensitive to weather are total deaths and elderly deaths (greater than 65 years old). For the total deaths in summer, the most important factors influencing mortality are the accumulation of degree hours above the threshold temperature each day and their time occurrence. Early heat waves in summer are more likely to have effects than those late in the season (Kalkstein, 1989). Correlation analysis between mortality and weather conditions in the US and Japan shows that mortality from several causes of death was also closely associated with air temperature (Kalkstein, 1989; Makino, 1987).

6.2.3 Air pollution

Global warming and elevation of UV-B radiation would accelerate photochemical reaction rates among chemical pollutants in the atmosphere, causing increased oxidants in many urban areas. In summer, high concentrations of oxidants are observed around many large cities throughout the world, frequently in excess of health-based ambient standards. Global warming may increase ozone concentrations in urban areas and spread the polluted areas even further, thereby increasing the health risk already posed to persons in those areas.

The main pollutants caused by photochemical reactions are ozone, oxides of nitrogen, aldehydes, peroxyacetyl nitrates, and propylene glycol nitrates.

Evidence exists to associate the photochemical oxidants with adverse effects on human health (Schneider et al., 1989). The diseases that fall into this category are inflammatory disease of the eye, acute non-specific upper respiratory disease, chronic bronchitis, chronic obstructive ventilatory disease, pulmonary emphysema, and bronchial asthma. Moreover, it is reported that ozone modifies lung tumour formation (Hassett et al., 1985; Last et al., 1987).

Many organic carcinogens are also common in the urban air. Since some of these chemicals are produced or decomposed by chemical reaction in the air, the concentration of these pollutants may be affected by global warming and UV-B radiation increase.

6.2.4 *Chemical pollution*

Global warming has potential impacts on crop yields and productivity. Since crop production is sensitive to water supply and plant pests, crop yields could change water supply and pest control management. Global warming may modify the incidence of plant pests and hazardous insect population. Changes in water supply could affect the agrochemical leaching from farms and degrade surface and groundwater quality in many areas.

Many types of pesticides are used to control plant pests and parasites. Since temperature increase may accelerate the volatilisation of many organic chemicals, the atmospheric transport of the chemicals may accelerate (Bidelman et al., 1981; Rapaport et al., 1985; Rovinsky et al., 1982; Tanabe et al., 1982). High temperature and elevation of UV-B radiation may accelerate the chemical reaction of organic pollutants in the atmosphere and the degradation rate of the chemicals. Therefore, global warming could influence the concentration of many organic pollutants in the environment thereby resulting in a change of human exposure (Ando et al., 1985).

6.2.5 *Water quality and quantity*

Global warming may change the timing and amount of precipitation in various countries. In the regions with less precipitation, salt concentrations in water may increase greatly. High salt concentration in water and reduction of water supply may directly affect the health of people in that area. If global warming reduces the precipitation, food production could decrease significantly (US EPA, 1988). Sometimes, the low food supply will increase famine and malnutrition in developing countries with potentially large consequences for human mortality. On the other hand, heavy rain also could decrease water quality. Sometimes, frequent flooding has threatened the health of people in developing countries, directly or indirectly. Permafrost degradation may cause leaching from disposed wastes, resulting in contamination of the groundwater. If global warming worsens the water quality or increases inundation, diarrhoea, cholera and dysentery epidemics could spread in developing countries and in the subarctic area.

6.2.6 *Vector-borne diseases*

Global warming may modify the incidence and/or distribution of vector-borne disease. If global warming changes rainfall and temperature, the seasonal and geographical abundance of the major vector species, such as mosquitoes, could change. In the Northern Hemisphere, these vector-borne diseases could move northward and in the Southern Hemisphere southward.

Some infectious diseases are well known to show apparent seasonal changes and would seem to be very sensitive to global warming. Japanese encephalitis and some other viral diseases are regulated by some seasonal factors. Therefore, an improvement of the environment may be necessary to prevent the breeding of vector species.

In tropical regions, vector-borne diseases have important impacts on morbidity and mortality. In 1988 malaria and schistosomiasis posed potential risks to 2100 and 600 million people, respectively. If global warming increases the precipitation in tropical and subtropical areas, many diseases may further threaten human health. Parasitic and viral diseases, such as malaria, schistosomiasis and dengue have the potential for increase and reintroduction in many countries (WHO, 1990; Dobson and Carper, 1989).

6.2.7 *Ultraviolet-B radiation*

UV-B radiation has many damaging effects on human health, such as skin cancer, cataract and snow blindness (Hiller et al., 1983). UV-B radiation also suppresses the immune defences against certain infections and tumours initiated in the skin.

There are two main types of non-melanoma skin cancer: basal cell carcinoma and squamous cell carcinoma, which have a convincing and clear-cut relationship to UV-B radiation (Blum et al., 1941; Blum 1959). Malignant melanoma is also at least partially caused by exposure to UV-B radiation. It has been recognised that the incidence of skin cancer including melanoma increases from high to low latitudes possibly due to the increase of UV-B radiation. In this connection, account must be taken of the changes that have occurred in recreational behaviour and people's willingness to expose themselves to the sun.

While it is difficult to estimate numerical effect on the basis of epidemiologic data in the US (US EPA, 1987), UNEP (1989) and WHO (1989) estimated that for every 1% decrease in stratospheric ozone, there will be between a 0.3% to 0.6% increase in cataracts. Based on the same epidemiologic date, it was also estimated that for every 1% depletion of ozone the incidence of basal cell carcinoma, squamous cell carcinoma and malignant melanoma, will increase 2.7%, 4.6% and 0.6%, respectively. There is concern that UV-B radiation, suppression of the immune system might lead to an increase of the incidence and severity of infectious diseases. It is necessary to confirm the incidence rate of skin cancer in various countries in relation to UV-B dose. Data on UV-B exposure dose is extremely limited.

6.3 Determination of sensitivities

6.3.1 General climate effect

Global warming may affect the seasonality of many causes of death. The seasonal variation of mortality also changes sharply according to the improvement of the environment and the socioeconomic condition of countries.

6.3.2 Heat stress

Global warming is likely to induce mortality increase during heat waves in summer. On the other hand, winter mortality may decrease. In general, weather-induced deaths are more important in summer than in winter. Artificial heating and cooling, when affordable, may reduce deaths from heat and cold.

The less resilient population - the poor, the disabled, the sick and the aged - are at greater risk.

6.3.3 Air pollution

Global warming and increased UV-B radiation would both accelerate the photochemical reaction rates among chemical pollutants and increase ozone concentration in urban areas. Ozone and other photochemical oxidants may be associated with many respiratory diseases and cancer.

6.3.4 Chemical pollution

Global warming may result in an increase of pesticide use in agriculture, and accelerate the volatilisation and atmospheric transport of many organic pollutants in global ecosystems.

6.3.5 Water quality

As global warming could change the precipitation, water quality may be affected greatly. High salt concentration and less water supply may threaten the drier land through impaired drinking water and food production. On the other hand, heavy rain will cause floods and spread water-borne diseases.

6.3.6 Vector-borne diseases

Since global warming changes rainfall and temperature, distribution and abundance of many vector species should change. Some infectious diseases including parasitic and viral diseases, such as malaria, schistosomiasis and dengue have the potential to increase in many countries, especially tropical and subtropical areas.

6.3.7 UV-B radiation

Since build-up of CFCs in the stratosphere may lead to stratospheric ozone depletion and increase UV-B radiation, a number of diseases of the eyes and skin, such as cataract, non-melanoma and melanoma skin cancer, may increase.

6.4 Tasks for the near future

The following research would be necessary:

6.4.1 General climate effect

(i) The effect of global warming on seasonal trends of major causes of morbidity and mortality,

(ii) The assessment of the incidence of major causes of death in industrialised and developing countries in the future.

6.4.2 Temperature stress

(i) The effect of global warming on heat and cold wave episodes;

(ii) Methods of decreasing mortality among high-risk groups;

(in) The assessment of capacity of adaptation to hot and cold weather, especially among vulnerable population groups such as the elderly.

6.4.3 Air pollution

(i) The effect of global climate change on oxidants and organic carcinogens in the atmosphere;

(ii) Exposure assessment of these air pollutants;

(iii) The incidence of respiratory disease and lung cancer in polluted and non-polluted areas.

6.4.4 Chemical pollution

(i) The effect of global warming on the worldwide chemical pollution;

(ii) Human exposure to these chemical pollutants;

(iii) The incidence of morbidity and mortality in acutely or chronically exposed populations.

6.4.5 Water quality

(i) The effect of global warming on the precipitation in various countries;

(ii) The assessment of hygienic quality of water resources in the world.

6.4.6 Vector-borne diseases

(i) The effect of global warming on geographical abundance of major vector species;

(ii) The assessment of incidence of vector-borne diseases in the future;

(iii) The improvement of the environment to prevent the breeding of vector species.

6.4.7 UV-B radiation

(i) The assessment of the elevation of UV-B radiation according to ozone depletion in order to determine the dose received;

(ii) Epidemiological association of the rise of incidence of cataracts, non-melanoma and melanoma skin cancer and an increase of UV-B radiation in many countries.

(iii) The risk evaluation of immune suppression by UV-B radiation increase on vaccination and infectious diseases.

7 Summary of likely impacts of global warming and stratospheric ozone depletion on air quality

This section addresses the effects on regional and tropospheric air quality resulting from climate warming and stratospheric ozone depletion.

7.1 Scope and limitations of the assessment

(See Figure 5.3.)

Change in air quality, photochemical ozone production, acid rain, visibility and albedo due to climate change and tropospheric temperature rise are assessed. However, the lack of reliable regional prediction of changes in circulation, precipitation, humidity, cloud cover, arid area, trace-gas concentrations etc hinders their quantitative assessment.

7.2 Assessment of impacts

The tropospheric temperature rise induced by the greenhouse effect could change homogeneous and heterogeneous reaction rates (Washida et al., 1985), solubility to cloud water, emission from marine, soil and vegetative surfaces and deposition to plant surfaces of various atmospheric gases including water vapor and CH_4 (WHO, 1989).

A change in water vapour concentration will lead to change in concentration of HO_x radicals and H_2O_2, which are important for the oxidation of volatile organic compounds (VOC), SO_2 and NO_x in the atmosphere.

Climatic change could induce change in pressure patterns, humidity, atmospheric stability, clouds, precipitation and distribution of arid lands. The predicted change of the patterns of cloud cover, stability in the lower atmosphere, circulation and precipitation could concentrate or dilute pollutants, and change their distribution pattern and transformation rates in local and regional scales.

A change in aerosol formation by atmospheric conversion from VOC, NO_x and SO_2 and windblown dust from arid land, and organic aerosol production from vegetation, could lead to changes in visibility, the planetary albedo and effect upon human health (WHO, 1989).

A change in energy usage due to fuel switching and increased use of air-conditioners will lead to changes in energy-related emissions.

All of the above changes will be linked to impose some effects upon air quality, ozone and aerosol production, visibility, global albedo and acid deposition in local, regional and global scales. Among these combined effects the effect of temperature upon ozone production has been studied most extensively.

Temperature-dependent modelling studies on ozone production were conducted by Gery et al. (1987), Morris et al. (US EPA, 1988), and MacCracken and Santer (1975). According to the studies by Gery et al. (1987) the increase in ozone is predicted to be about 1.4 ± 0.5% per IK increase. The production of H_2O_2 is predicted to increase at a much higher rate. The model calculation also predicted increased ozone production with the depletion of stratospheric ozone. In the San Francisco Bay area Morris concluded that 4K of temperature increase resulted in a 20% increase in peak ozone concentration and about a doubling of the area in exceedence of the national ambient air quality standards (120 ppb). On the other hand, MacCracken and Santer indicated that for the San Francisco Bay area the LIRAQ model showed 2% decrease in peak ozone with a nominal temperature increase from 285K to 304K. Wratt (1989) predicted that in Auckland temperature increases of 1.5K and 3.5K would increase peak ozone concentration by 8% and 19%, respectively. A recent modelling analysis conducted by the US EPA showed that for a maximum average temperature rise of 2.5K, the increase in peak ozone would be between 2% and 10% for various urban locations throughout the US.

Smog chamber studies conducted by Carter et al. (1979) and by Hatakeyama et al. (1989) found increases in peak ozone concentration with the rise of temperature from experimental temperature of 280K to 320K and of 303K to 323K, respectively. The chamber experiments supported a view that the time of exposure to high levels of ozone would be increased in the region of higher temperature. In smog chamber experiments Johnson (1983) found that photochemical smog increases with temperature, provided that photochemical smog production is in the so-called 'light-limited' phase and not the 'NO_x limited phase.'

While some different results were obtained, a majority of the studies indicate the potential for increased ozone production with increasing temperature in industrialised urban areas. Since higher temperature increase is predicted at higher latitudes, much attention should be paid to the increased ozone production in such areas. In developing countries, ozone pollution may be limited to the largest cities, but the extent of the problem may expand, given the explosive growth of urban area in those parts of the world. It is well accepted that increased levels of local and regional air pollution, particularly photochemical air pollution, may exert effects upon human health and terrestrial plants. In addition, acid rain could affect sensitive areas in Europe, the northeastern US, Canada and some areas of east Asia, where acidification of lakes and forest damage may occur. Material damage caused by acidic and other kinds of air pollutants may be aggravated by higher levels of humidity.

7.3 Determination of sensitivities

Severalfold increases of natural emissions or atmospheric concentration of trace gases with a temperature rise of 10K have been observed in specific locations by various researchers. For example, the following increases were noted for NH_3 (3.1), DMS (9.0), H_2S + COS (4.1), NO (3.3) and terpenes (6.0). (Figure in parenthesis is factor of multiplication for each compound of the gases with temperature rise of 10K.) (Okita and Kanamori, 1971; Aneja et al., 1979; Tingey et al., 1981; Johansson and Granat, 1984.)

The average increase of peak electricity demand due to increased use of air-conditioners with temperature rise of IK is about 3%. US EPA (1988) calculated that a 10% increase in electric power demand increases SO_2 emissions by 30%. However, as patterns of power output are different in different regions, care should be taken in applying this figure to other areas.

Impacts on energy usage are likely to vary in winter and summer. In the Tokyo area, overall electricity consumption is decreased by 0.9% in winter and increased by 2.7% in summer with IK rise of air temperature (Tokyo E.C., 1988). Using non-linear regression analysis, Wratt predicted that at Christchurch, New Zealand, with minimum temperature rise of 1.8K and 3.0K mean TSP (total suspended particulates) from domestic fire smoke would decrease by 14% and 19%, respectively.
A temperature rise of 2K would raise water vapour concentration by 10%-30%.

7.4 Tasks for the near future

Changes in the frequency and pattern of cloud cover owing to the greenhouse effect should be studied in relation to ozone formation and conversion of SO_2 and NO_x.

Change in pressure, wind, circulation and precipitation patterns and the frequency and intensity of stagnation episodes due to the greenhouse effect should be studied in relation to the change in distribution of air quality, oxidants and acid rain.

Quantification should be made of the effect of atmospheric temperature on photochemical oxidant formation and on acid rain. Particularly, the discrepancy between model prediction and the results of photochemical smog chamber experiments in different levels of NO_x should be pursued.

The temperature dependence of energy use in various sectors other than electricity, due to global warming, should be studied in relation to its effect upon acid deposition and photochemical ozone formation.

Change in the extent of arid regions should be studied in relation to generation of windblown dust and its effect upon air quality, acid rain and planetary albedo.

Change in oxidant formation in remote areas due to the greenhouse effect should be studied, taking the change of emission of precursor gases into account. Interaction of climate factors and emission of dimethylsulphide should be studied to prove or refute one of Lovelock's Gaia hypotheses.

The temperature dependence of homogeneous reaction rates, and reaction rates in aqueous phase of atmospherically important gaseous species should be more accurately quantified.

More study should be made on the temperature dependence of emissions of important gases from soil, sea surface and plants.

GCMs and mesoscale meteorology-chemistry models which include the above effects should be linked to predict overall effects of GHG.

8 Summary of likely impacts of increased UV-B radiation

This section summarises the effects of UV-B radiation, resulting from the depletion of the stratospheric ozone layer, upon ecosystems, air quality and materials.

8.1 Scope and limitations of the assessment

(See Figure 5.4.)

This section discusses the potential influence of the greenhouse effect upon stratospheric ozone depletion. The potential impacts of UV-B radiation arising from the ozone depletion on terrestrial vegetation, marine organisms, air quality and materials are also analysed. The UV-B impact upon human health has been described in the section on health. However, the lack of data on the dose received of UV-B hinders a quantitative assessment of impacts.

8.2 Assessment of impacts

It is expected that the depletion of the ozone column due to anthropogenic activities incrcaAM UV-B radiation. The UV-B range of the vjlar tp-tctrum *n* defined as wavelengths from 290 to 320 nano-ni.c.vtt (nm). On the other hand, the greenhoiiat ***tUssl-*** induced global warming will, wm.c *tacnijzti* bt/.ur<^ decrease stratospheric ***temperutixit*** and ***mx'i*** r.im-press the ozone depletion (Manafce ajwd ViV-te?*-*-^ 1967).

Investigations have shown that L*V-£ ***m.i..n\ai*** a multitude of effects on humans., t.eTTtv'j''..iJ vagsution, marine organisms, air quality and csc.sr.Aji: most of these effects are damaging fWHG. However, no exact measurements on the relaiiocai-y between UV-B intensity near the ground and the amount of ozone in the stratosphere and troposphere has been established.

Research into the potential impacts of an increase in solar UV-B radiation to plants has centred on the effects on plant growth and physiology under artificial UV-B irradiation supplied to plants in growth chambers or greenhouses.

Overall, the effective UV-B varies both among species and among cultivars of a given species. Sensitive cultivars of soybean, wheat, oat, cucumber, sunflower etc, often exhibit reduced growth, photosynthetic activity, pollination, germination and flowering. Photosynthetic activity may be reduced and photosynthetic pigments are also affected by UV-B (Tevini and Teramura, 1989).

Increases in UV-B radiation reduce yield in certain agricultural crops. Many soybean cultivars are sensitive to increased UV-B radiation. The crop quality may be reduced under increased levels of UV-B radiation. Reduced quality has been noted in certain cultivars of tomato, potato, sugar beets and soybean (Tevini and Teramura, 1989).

Although only limited information exists, gymnosperms also appear to be sensitive to UV-B radiation (Sullivan and Teramura, 1988).

Water stress in combination with UV-B adversely affected water loss in cucumber cotyledons (Takeuchi and Hayashida, 1987).

Increased solar UV-B radiation could reduce the productivity of the phytoplankton, with dramatic effects both for intricate marine ecosystems. An% reduction of this marine productivity will undoubtedly affect global food supply (Damkaer, 1^"V

Recent studies have shown that UV-B impairs motility in a number of micro-organisms; any decrease in orientation of motile phytoplankton prevents the necessary constant adaptation to the changing environmental conditions and possibly hazardous situations (Hader and Hader, 1988a, 1988b and 1989).

UV-B radiation also affects growth and the rhythm of many microorganisms (Worrest, 1982). Studies have also found that UV-B radiation drastically affects nitrogen fixation and thus the growth and productivity of higher plants in a number of important phytoplankton species (Dohler et al., 1985). Various experiments have demonstrated that UV-B radiation causes damage to fish larvae and juveniles, shrimp larvae, crab larvae, copepods, and plants essential to the marine food web (US EPA, 1987). There is also evidence that an increase in UV-B could diminish the growing season of invertebrate zooplankton populations (Damkaer et al., 1980).

The effect of increased UV-B on the air quality of remote areas should be a decrease in the already low surface ozone concentrations (Liu and Trainer, 1988). Results from several modelling studies and one chamber study suggested that increased UV-B radiation from ozone depletion may increase the rate of urban ozone formation (Whitten and Gery, 1986; Gery et al., 1987; Morris et al., 1988). Preliminary results from the modelling studies also suggested that large increases in hydrogen peroxide would result from increased UV-B radiation. One study has shown that hydrogen peroxide increases can produce increases in the formation of acid precipitation.

Higher levels of short wavelength radiation below 295 nm will lead to a significant acceleration of light-induced degradation processes of plastics and other coatings used outdoors.

8.3 Determination of sensitivities

One soybean cultivar showed a yield loss of up to 25% following exposure to UV-B radiation simulating a 5% ozone reduction (Tevini and Teramura, 1989).

In one study involving anchovy larvae, a 20% increase of UV-B radiation resulted in the death of about 8% of the annual larval population (Hunter et al., 1982).

Based on one assessment (using the relationship that fisheries yield increases as productivity is raised to the 1.55 power), a 5% decrease in primary production (estimated for a 16% ozone depletion) would yield reductions in fish yield of approximately 6% to 9%.

A 10% decrease in phytoplankton biomass equals 1014 kg and leaves the same amount of CO_2 in the atmosphere as annual fossil-fuel burning (5Gt) (Hader, 1980).

8.4 Study tasks for the near future

8.4.1 UV-B radiation

Trends of UV-B radiation should be studied and correlated to ozone trends.

More detailed measurements of the wavelength dependence of UV-B radiation should be made.

Efforts should be made to improve the standardising of instrumentation and calibrations of UV measurement.

8.4.2 Terrestrial plants

The number of field experiments for impacts of UV-B on agriculture should be increased.

Studies must be initiated to determine the impacts of UV-B to natural ecosystems.

UV-B effects on growth and reproductive cycles of lower plants, such as mosses, fungi and ferns, have yet to be studied.

Increase the effort taken to obtain a better understanding of the effects of multiple stresses and of shifts in competitive balance when plants are given additional UV-B.

An area of worldwide interest may be tropical rice-growing regions, where information is limited on how rice will be affected either under enhanced UV-B or under increased temperature and $C0_2$.

8.4.3 Aquatic ecosystems

Establish the effect of UV-B stress to aquatic microorganisms on commercial fisheries.

Determine the threshold of effect and biological action spectra for aquatic organisms.

Determine long-term effects for embryos or larvae exposed to UV-B radiation.

Determine effects on ecosystems, including the antarctic ecosystems.

Obtain data on the mechanisms of damage, and range of possible adaptation or genetic selection, in response to increased UV-B radiation.

Develop predictive three-dimensional models for loss in biomass production with CO_2 increase, including the enhancing effect of temperature increase.

8.4.4 Tropospheric air quality

For the ozone formation and destruction problem, the main research areas are: peroxides, photodissociation reactions of compounds that absorb UV-B, and aerosol formation.

Expanded modelling is needed to understand the effects of increased UV-B on tropospheric air quality and model predictions should be verified experimentally.

8.4.5 Materials damage

A comparative study is needed of environmental photodegradation of relevant plastic materials under near-equator and high-latitude conditions.

A study should be initiated to quantify the effect of UV-B radiation on non-plastic materials such as paints and coatings, rubber products, wood and paper products, and textiles.

Set up long-term weathering studies in different geographical regions to study the effects of naturally occurring variations in UV content of sunlight.

Undertake investigations of surface coating, painting and other means of controlling photodegradation including a study of environmental impact of such technologies.

Figure 5.1 Examples of possible energy impacts of climate changes

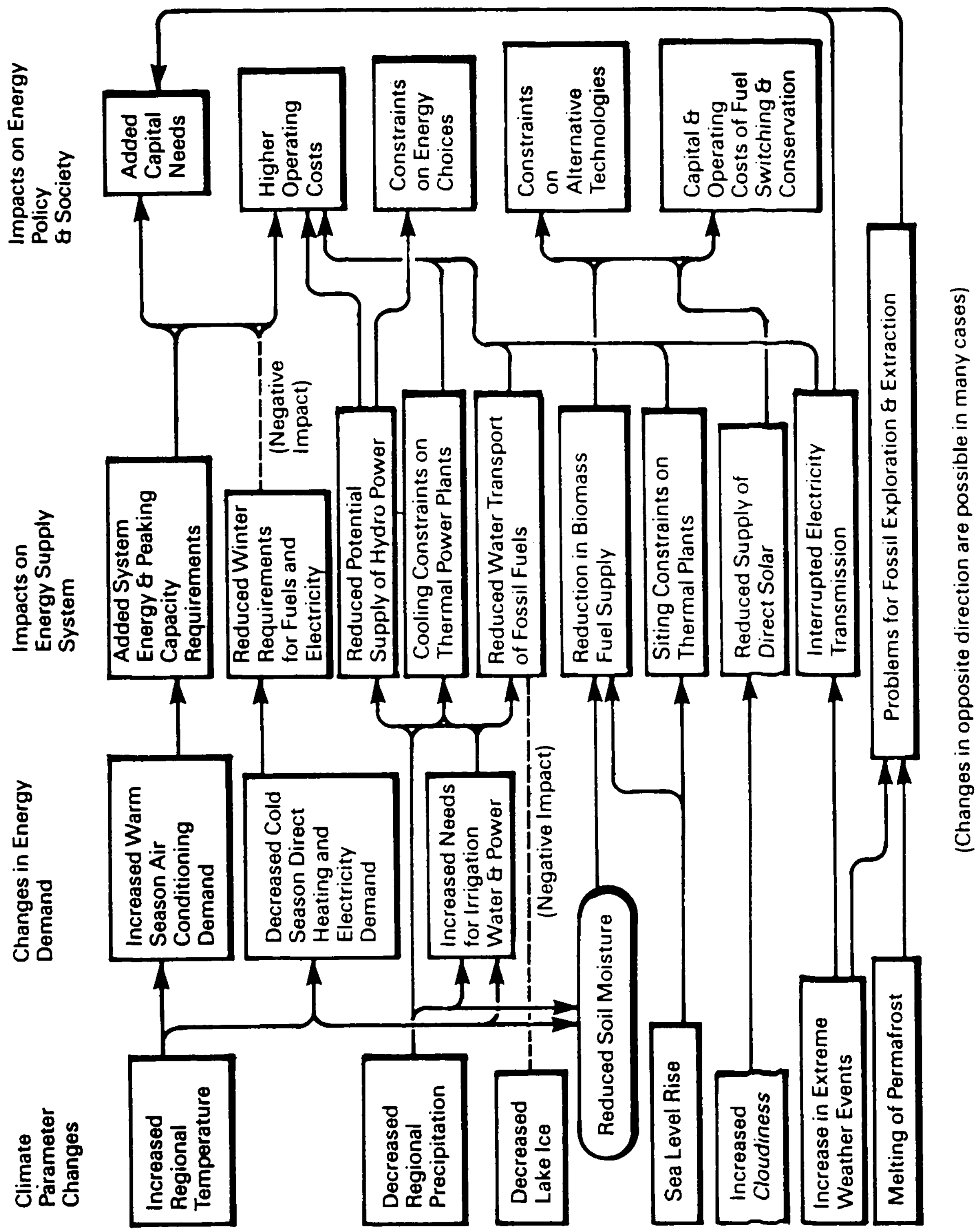


Figure 5.2 Impacts of climate change on health

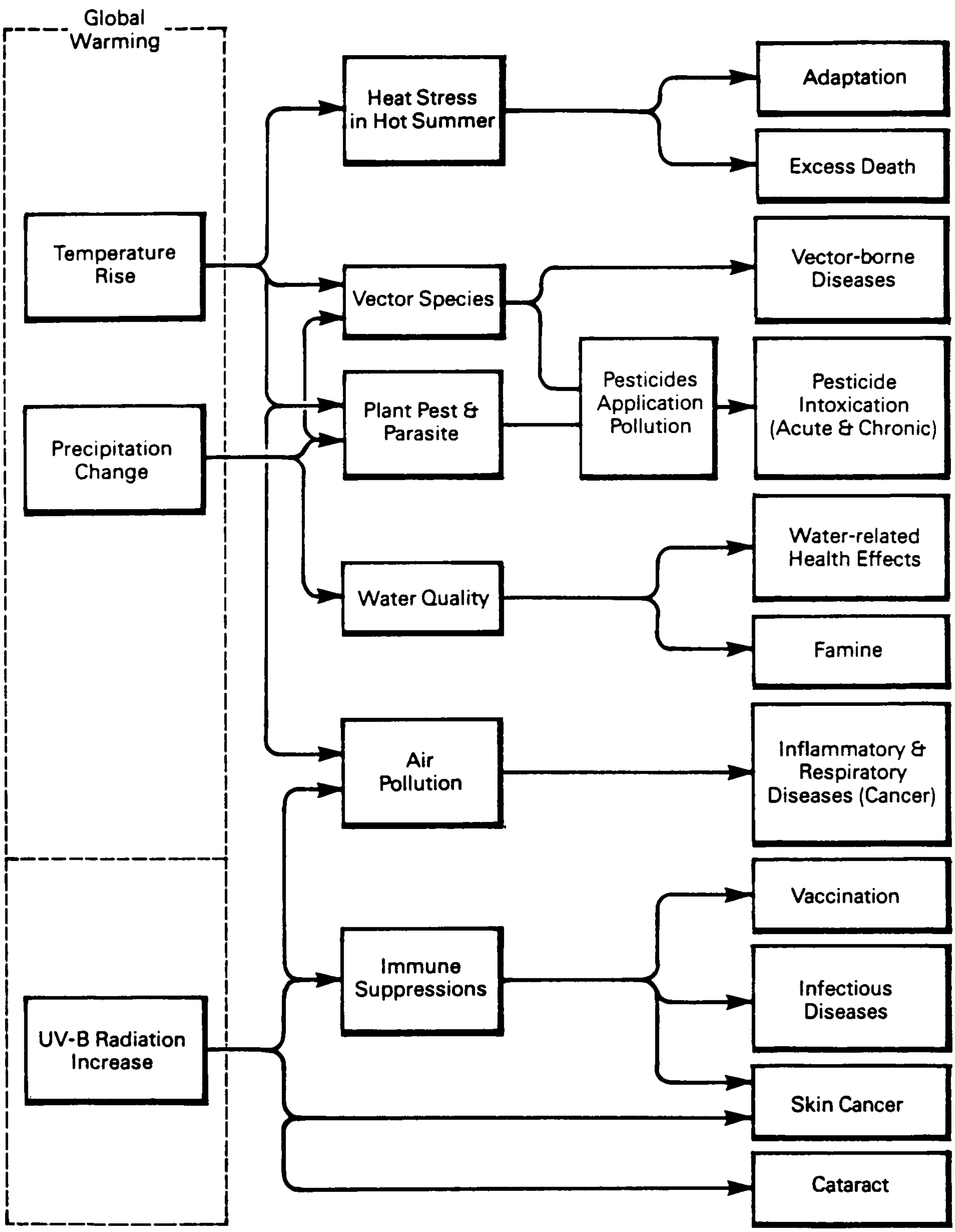


Figure 5.3 Effects of climate change on air quality

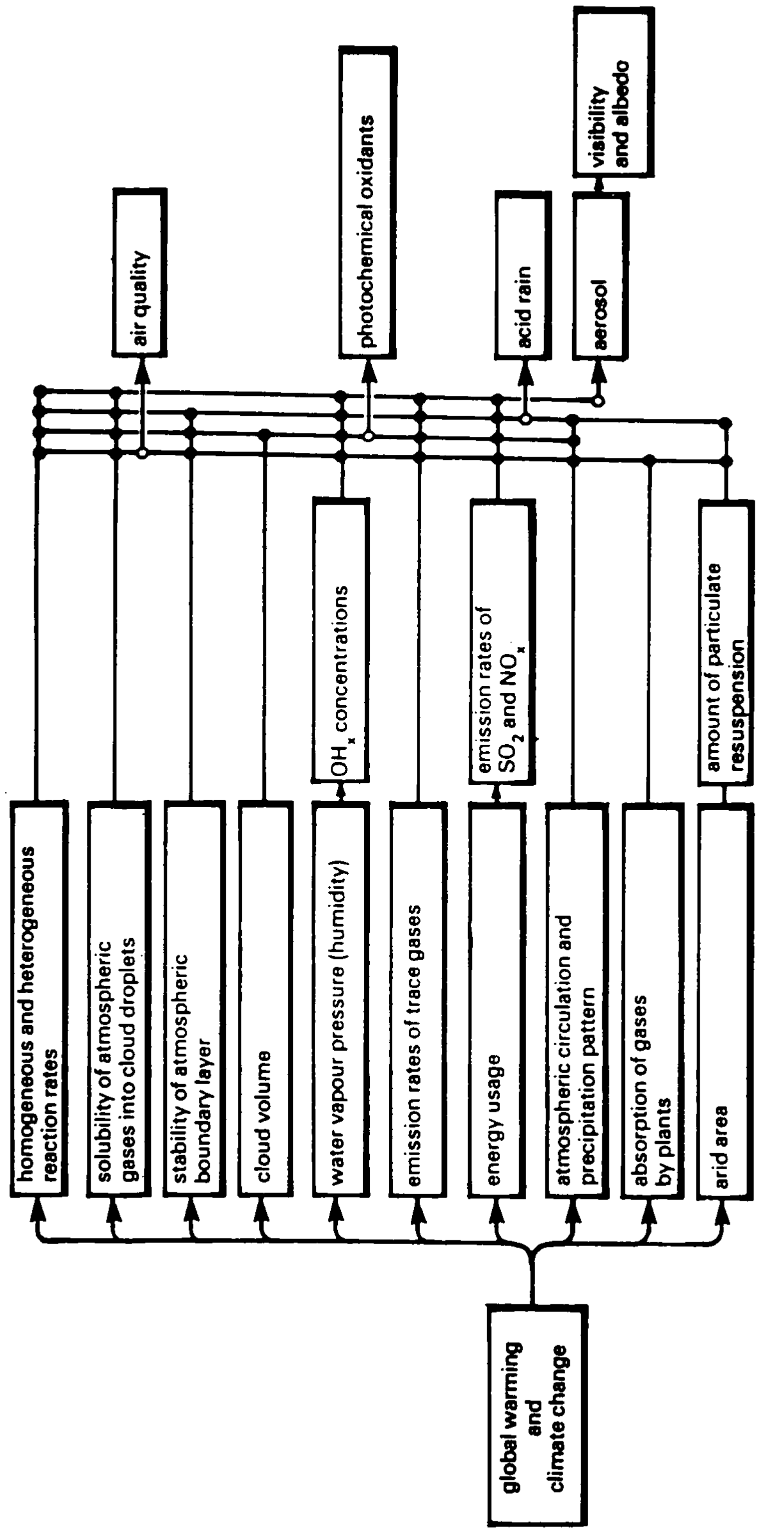
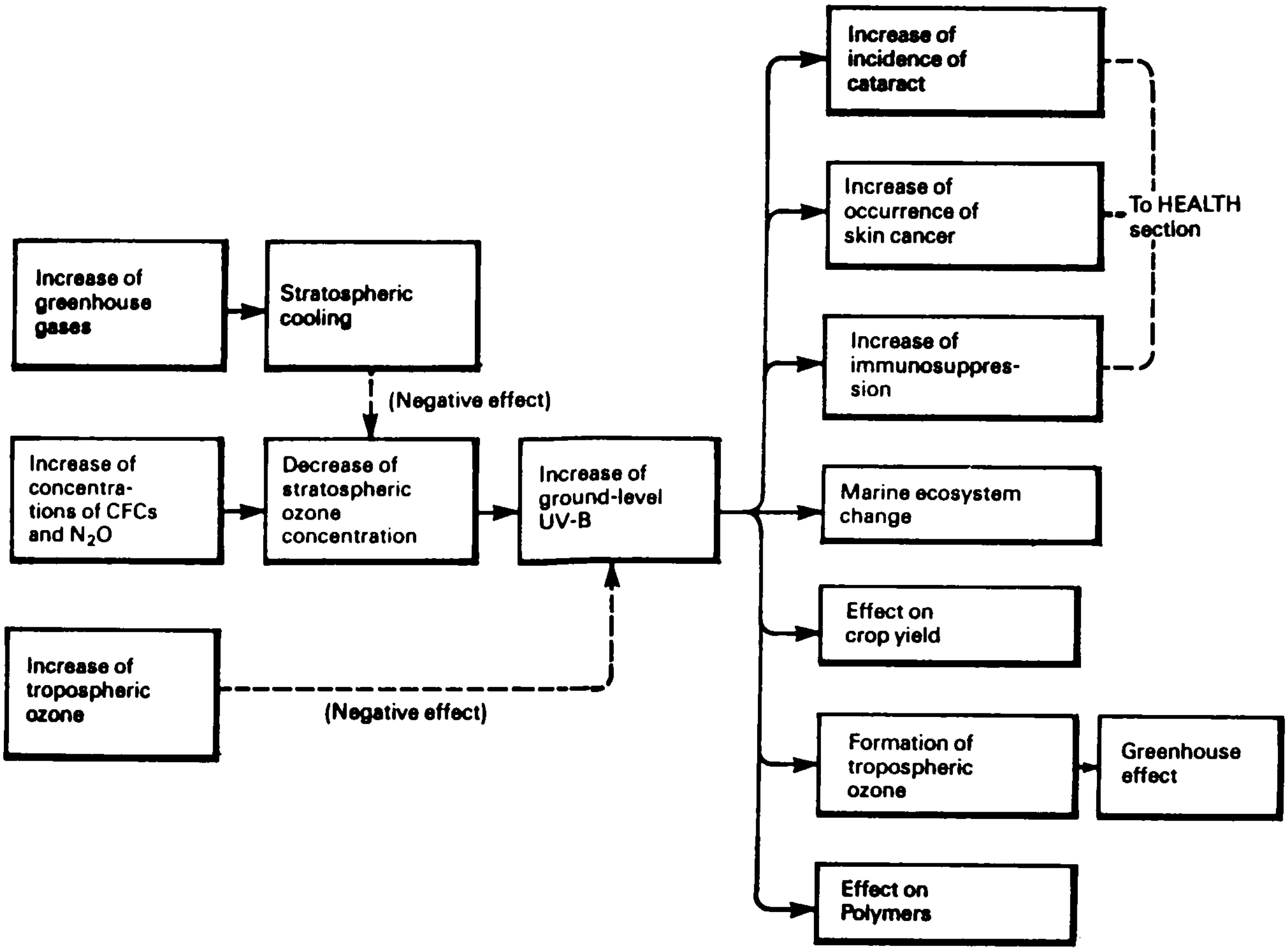


Figure 5.4 Scope of the assessment on UV-B radiation and secondary effects on human health and the environment



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Chapter 6

World oceans and coastal zones

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1 Introduction

Climate change will have significant impacts on the oceans of the world and the coastal zone, which will also play an important part in determining the nature and extent of climate change. Probably the most important aspects of climate change on the World Ocean and coastal zones will be the impact of sea-level rise on coastal residents and on marine ecosystems. These impacts are treated first, followed by the other impacts of climate change on the ocean and coastal zone.

The following assumptions were made in this report:

- carbon dioxide (CO_2) will double by 2050;
- other greenhouse trace gases will increase significantly;
- average world air temperature will increase by 1.5°-4.5°C;
- sea-level will rise by 0.3-0.5 m by 2050; up to about 1 m by 2100;
- there will possibly be an increase in solar ultraviolet-**B (UV-B)** radiation.

IPCC Working Group I scenarios were developed in parallel with the preparation of this report and are generally consistent with the assumptions of this report. However, a few of the cited studies with respect to sea-level rise have considered higher rates than those projected by Working Group I. This is useful information, given that there are important regional differences expected in sea-level rise because of such things as regional land subsidence, glacial rebound and oceanic currents (Mikolajewice et al., 1990), and the possibility of continuing natural processes such as polar ice sheet response to the last glaciation (NASA, 1990).

2 The socioeconomic and ecological impacts of sea-level rise and related climate change

2.1 Introduction

Future global warming could increase the rate at which sea-level has been rising by (i) warming and thereby expanding ocean water, (ii) melting mountain glaciers, and (iii) possibly causing polar ice sheets in Greenland and perhaps Antarctica to disintegrate. Current estimates are that sea-level will rise between 30-50 cm by the year 2050 and possibly up to 1 m by the year 2100 (Figure 6.1). Site-specific studies must add current trends in subsidence or emergence to these estimates. In addition, global warming may increase storm frequencies and intensities.

A rise in sea-level would (i) inundate and displace wetlands and lowlands, (ii) erode shorelines, (iii) exacerbate coastal storm flooding, (iv) increase the salinity of estuaries and threaten freshwater aquifers and otherwise impair water quality, (v) alter tidal ranges in rivers and bays, (vi) alter sediment deposition patterns, and (vii) decrease the amount of light reaching water bottoms (Figure 6.2).

Present population growth and development in areas subject to natural water-related hazards is itself a reason for concern. The foreseeable consequences of global warming and sea-level rise heighten concerns for countries and their citizens occupying these vulnerable areas. Other aspects of a countrys economic and social well-being may be adversely affected by fundamental changes to its fisheries and agriculture or its economic base in tourism. Also, in some countries, beaches and other coastal features provide important cultural values which may be threatened by sea-level rise. Further, there may be impacts on biodiversity as some small localised habitats are lost or move faster than the plants or animals which depend on them can adjust.

The present trend towards increasing deterioration of coastal areas through pollution, development and overuse (GESAMP, 1990) are also reducing the capacity of coastal systems to respond to and compensate for climate changes and sea-level rise.

After discussing the methodological limitations of existing knowledge, this chapter divides the impacts of sea-level rise into three categories:

(i) socioeconomic impacts (threatened populations in low-lying areas and island nations);

(ii) ecological impacts (alteration and degradation of the biophysical properties of beaches, estuaries, and wetlands);

(iii) physical aspects of shoreline retreat.

2.1.1 Methodological limitations

This chapter relies on previously published analyses that are based on a variety of sea-level scenarios. Many project a i m sea-level rise which Working Group I estimates will not be reached before the year 2100. There are far fewer studies which have looked at a rise of 0.5 m or less amount.

Because of inadequate data and the uncertainties regarding global warming, sea-level rise and future coastal development, the studies cited herein deal with possibilities, not forecasts. It is particularly difficult to assess the potential impacts consistently for all coastal regions.

Another problem facing all impact analyses is the need for baseline scenarios - in this case, what would happen without global warming (Stakhiv and Hanchey, 1989). Unfortunately, most sea-level rise studies (a notable exception is Gibbs, 1984), have ignored this issue and have generally assumed the current level of coastal development (eg Park et al., 1989; Delft, 1990a). The failure to consider future coastal development may have led these studies to underestimate the socioeconomic and environmental impacts of rising sea-level. Finally, there is little consistency regarding the probable response of society.

The purpose of this section is to assess the impacts of sea-level rise assuming (i) that people take rational but ad hoc actions and (ii) that governments take no organised response. Unfortunately, many of the studies cited do not follow this convention.

2.2 Socioeconomic impacts: threatened populations in low-lying areas and island countries

A simple measure of a country's vulnerability to sea-level rise is the proportion of its population and productive land that is within a few metres of present mean sea-level. A direct relationship exists between inundation (extended by the impacts of climate variability, storm surges, waves and erosion) and the viability of inhabited areas. Health, safety and food security are among the primary determinants of socioeconomic well-being. Threats to these attributes of well-being define a region's vulnerability. Not all countries are equally vulnerable and many will be only indirectly affected by sea-level rise, with limited impacts to a particular sector of the economy (eg fisheries, tourism) or affecting the mechanisms of trade and transportation (eg waterways, ports, inlets).

Coastal areas, particularly low-lying areas exposed to the open ocean are inherently hazardous, yet they have attracted people, industry and commerce. Every year lives are lost, tens of billions of dollars of damages are sustained, and hundreds of square kilometres of land are eroded. For most inhabitants who have a choice, the perceived benefits of living in this highly variable zone outweigh the risks and costs. Many are not so fortunate - they do not have the choices available to them. Thus, much of the dense coastal infrastructure in place today will probably be protected to the extent technically and economically feasible. Retreat would be more likely in less developed areas (Moser and Stakhiv, 1989; Dean et al., 1987; Barth and Titus, 1984).

Estimating monetary impacts is fairly straightforward; it is much harder to assign market values to non-monetary impacts (morbidity or mortality, ecosystem damage). Jansen (1990) reviewed methods of quantifying each. He discussed preventative policy measures, which are global and long term, and adaptive measures that can be more easily implemented nationally or locally. The few studies on economic assessment of sea-level rise estimate the engineering cost only.

Data on vulnerability to damage (altitudes of vulnerable areas, existing buildings and infrastructures) vary widely from country to country. The following sections examine the socioeconomic implications of inundation, erosion, agricultural losses, increased flooding and the impacts of water supply, water quality and infrastructures.

2.2.1 Inundation

The direct effect of inundation is the potentially large loss of inhabited areas, particularly in low-lying, flat deltaic and estuarine areas. Half of humanity inhabits the coastal regions around the globe, and large areas of highly vulnerable flood-prone sections are densely populated. A i m rise in sea-level could inundate 12-15% of Egypt's arable land (Broadus et.al., 1986) and 17% of Bangladesh (Commonwealth Secretariat, 1989). Large displacements of population would be likely in Indonesia and Vietnam. The United States would lose 20,000 km^2 kilometres of land, an area worth about $650 billion (Park et al., 1989; Yohe, 1990).

In extremely flat deltaic areas, a i m rise in sea-level would cause shores to retreat several kilometres, displacing hundreds of villages and depriving millions of people of their means of subsistence, ie their lands and natural resources. A group of experts convened by the Commonwealth Secretariat (1989) reported that the most vulnerable deltas include:

the Nile in Egypt, Ganges in Bangladesh, the Yangtze and Hwang Ho in China, the Mekong in Vietnam, the Irrawaddy in Burma, the Indus in Pakistan, the Niger in Nigeria, the Parana, Magdalena, Orinoco and Amazon in South America, the Mississippi in the US and the Po in Italy.

Many small island countries would lose a significant part of their land area with a sea-level rise of 1 m (Lewis, 1988). Coral atoll nations, such as Kiribati, Marshall Islands, Tokelau and Tuvalu, Cocos and Keeling Islands, are particularly vulnerable to inundation and erosion because they are generally below 3 m elevation and narrow, implying few possibilities for retreat. Coral reefs along many tropical coasts serve as natural breakwaters. Any sea-level rise will allow waves to over-top the reefs, increasing coastal vulnerability to erosion and storms, at least until reef growth can catch up with sea-level. The more rapid the rate of sea-level rise, the longer the period of vulnerability, and the greater the possibility that present reefs will be unable to catch up and that they will drown. Coral mining for building materials, and land reclamation on coral reef flats increase the risk of damage.

Some scientists (eg Parnell, 1989) have suggested that increased growth rate of coral reefs and more efficient sedimentation processes may offset some of the sea-level rise effects for atolls, at least for the next 50-100 years. Further research and study are clearly needed.

The 1190 small islands making up the Republic of the Maldives barely rise 2-4 m above sea-level (Small States Conference on Sea-level Rise, 1989.). A recent UNEP report on the republic (Pernetta and Sestini, 1989) illustrates the dilemma facing atoll countries. The Maldives already experience serious environmental degradation, primarily because of the high population density on the few inhabited islands within each atoll.

In a recent survey, Delft Hydraulics Laboratory (1990a, 1990b) attempted a first-order estimate of 181 coastal countries and territories. The study estimated that 345,335 km of low coast, 6400 km of urban waterfronts, 10,725 km of sandy beaches, and 1756 km^2 of harbour areas would have to be protected. Many of the island countries do not have the alternative of retreat and must either protect themselves or evacuate the islands. Table 6.1 shows the annual costs of preventing inundation and erosion as a percentage of the country's GNP. For ten countries, nine of which are islands, the estimate of annual costs would comprise greater than 5% of their GNP. Because the study assumed that all low land areas with population density greater than 10 inhabitants per km^2 would be protected, protection costs may be overstated. On the other hand, the total cost of sea-level rise may be underestimated because coastal areas are still being developed and the study did not consider the value of lost wetlands, dry land that would not be protected, or the cost of correcting problems due to increased flooding or saltwater intrusion.

2.2.2 Agricultural losses

Sea-level rise could decrease the agricultural productivity of many deltaic countries that can least afford the losses (Bangladesh, Egypt, China etc). The impacts on agriculture arise not only from direct loss of arable land to inundation, but also to the increased potential for erosion and increased coastal and riverine flooding. For example, about 20% of agricultural production could be lost, mainly rice, sugarcane and jute, as a result of the 1 m inundation of Bangladesh (UNEP, 1989). Similarly, about 15% of Egypt's agricultural production would be permanently lost. Thailand and China are regarded as being especially vulnerable to significant losses of productive deltaic agricultural land, as are Gambia, Senegal, Nigeria and Mozambique. Additional land could also be degraded by salinisation and flooding.

Differing interests may cause conflict and dispute over property rights and responsibilities. Farmers losing land to sea-level rise can get land only from others to compensate for their loss. Since vacant agricultural land is scarce, the result could be ruin for farmers hit by the effects of land loss. The problems can be tremendous in countries where large populations and areas are seriously hit.

2.2.3 Erosion and tourism

In many areas, the total shoreline retreat from rising sea-level would be greater than that due to inundation alone, because land well above sea-level could also erode. In the US, several studies have concluded that a 30 cm rise would eliminate the existing recreational beaches at most major resorts and threaten ocean-front property worth tens of millions of (US) dollars per kilometre of shoreline (Kana et al., 1984; Leatherman, 1985; Titus, 1986; 1990). The Miami and Perth IPCC coastal workshops suggested that sea-level rise would also threaten oceanside development in Portugal, Brazil, Nigeria, Thailand and most other nations with tourist beaches.

2.2.4 Increased potential of coastal flooding

Coastal storms can threaten human life, livestock, crops, structures and water supplies. As sea-level

Table 6.1 Survey of 1 m sea-level rise and protection costs. (Countries and territories ranked by estimated costs as per cent of GNP*)

No	Country or territory	Annual cost as % of GNP	Length low coast (km)	Beach length (km)
1	Maldives	34.33	1	25
2	Kiribati	18.79	0	0
3	Tuvalu	14.14	0	0
4	Tokelau	11.11	0	0
5	Anguilla	10.31	30	5
6	Guinea-Bissau	8.15	1240	0
7	Turks and Caicos	8.10	80	5
8	Marshall Island	7.24	0	0
9	Cocos (Keeling) Isl	5.82	1	0
10	Seychelles	5.51	1	25
11	Falkland Isl	4.75	1	0
12	French Guiana	2.96	540	0
13	Belize	2.93	500	0
14	Papua New Guinea	2.78	6400	0
15	Bahamas, the	2.67	400	200
16	Liberia	2.66	2200	0
17	Gambia, the	2.64	400	0
18	Mozambique	2.48	10015	25
19	St.Chr. and Nevis	2.33	40	10
20	Nieu	2.18	6	0
21	Guyana	2.12	1040	0
22	Suriname	1.94	2800	0
23	Sierra Leone	1.86	1835	0
24	Aruba	1.85	1	15
25	Pitcairn Island	1.71	0	0
26	Fiji	1.53	11	25
27	Sao Tome and Pr.	1.46	3	5
28	Nauru	1.25	3	0
29	British Virgin Isl	1.24	1	10
30	Tonga	1.14	4	0
31	Cayman Islands	1.04	1	25
32	Cook Islands	1.03	0	0
33	Equitorial Guinea	1.02	7	0
34	Antiqua and Barbuda	1.01	50	10
35	Sri Lanka	0.89	9770	30
36	Togo	0.87	300	20
37	St Lucia	0.82	25	10
38	Burma	0.77	7470	0
39	Benin	0.74	485	10
40	Micronesia, Fed. St.	0.73	0	0
41	New Zealand	0.70	14900	100
42	Palau	0.69	7	0
43	Grenada	o.67	6	5
44	Neth. Antilles	0.66	25	30
45	Senegal	0.65	1345	0
46	Ghana	0.64	2400	20
47	Somalia	0.62	700	0
48	Western Samoa	0.59	11	0
49	Madagascar	0.56	1190	0
50	St. Vincent and Gr.	0.55	7	5

* This estimate does not represent the total cost of sea-level rise, only the cost of erecting shore protection structures.

rises, these damages could increase substantially as the most densely populated areas landward of the present shoreline come under the direct influence of storm surges and wave attack. Sea-level could increase the risk of flooding for three reasons: (i) there would be a higher base upon which storm surges would build; if sea-level rises 1 m, an area flooded today with 50 cm of water every 20 years would then be flooded with 150 cm every 20 years; surges would penetrate further inland (Kana et al., 1984). (ii) beaches, sand dunes, coral reefs, marshes and mangroves currently protect many areas from direct wave attack; by removing these protective barriers, erosion would leave many areas more vulnerable; and (iii) sea-level rise would increase flooding from rainstorms and river surges owing to decreased drainage (Titus et al., 1987).

The higher base for storm surges would be particularly important in areas where hurricanes or severe storms are frequent, such as the southeastern US, the Indian subcontinent, the western Pacific and islands in the Caribbean Sea. Wynne (1989) estimates that even a 50 cm rise would cause areas in South Australia, flooded today only once per century, to be flooded every two years. In Japan, a i m rise would threaten an area of 1700 km^2 square kilometres in which 4 million people live (Mansfield and Nishioka, 1989).

Floods in Bangladesh would be worse for all of these reasons. In 1987, for example, flood crests of the Ganges and Brahmaputra rivers coincided in Bangladesh, inundating about one third of the country and forcing tens of millions of people from their homes. In addition, about ten million people live on land that lies within 1 m of mean sea-level near the coast. The coastal plains of Guyana, which also he at the high-tide level, are inhabited by 90% of the population. The coastal defence system has deteriorated and is vulnerable to sea-level rise. Finally, the Pacific and Indian Ocean atoll countries would be especially threatened by the increased flooding from a combination of sea-level rise and the possibility of the increased frequency and magnitude of coastal storms and cyclones (Emmanuel, 1988).

Other possible associated effects of global warming could also increase coastal flooding. In particular, increases in the frequency and magnitude of riverine floods and coastal storms could result from changing weather patterns, increased precipitation, and shifting of the seasonality of monsoons, snowmelt and other precipitation - runoff phenomena. The resultant wetter soils and increased flows could exacerbate flooding and result in the loss of agricultural productivity, as the soils stayed saturated for longer periods.

2.2.5 Water supply and quality

Sea-level rise would generally enable salt water to advance inland in both aquifers and estuaries. Particularly during droughts, the upstream migration of salt fronts in estuaries would threaten municipal and industrial freshwater intakes that draw water from tidal rivers for water supply. In the US, a 50 cm rise would enable salt water to advance 10-20 km upstream in the Delaware Estuary, threatening Philadelphia's municipal intake, as well as adjacent aquifers that are recharged by the (currently fresh) river water (Hull and Titus, 1986); New York (Miller et al., 1988), Southern California (Williams, 1989) and coastal cities throughout the world relying on freshwater intakes that draw water from tidal rivers would be similarly vulnerable.

Saltwater contamination of municipal water supplies could also occur more frequently than under historical drought periods. Even in areas where the General Circulation Models (GCM) predict a net increase of mean annual precipitation, the models also suggest a progressive increase in the frequency of droughts to the year 2050. Not only could municipal water supplies be contaminated more frequently, at the most critical times, groundwater aquifers could also be contaminated by saltwater intrusion. In addition, a good deal of agricultural irrigation water is withdrawn from the streams and rivers. Hence these supplies would also be adversely affected by extended periods of saltwater intrusion, also during the critical drought periods.

A particular concern facing atoll countries is the impact of sea-level rise on groundwater availability. Countries such as Kiribati, Marshall Islands, Tokelau and Tuvalu in the Pacific, and the Maldives, Cocos and Keeling Islands in the Indian Ocean depend on rainwater lenses that lie atop salt water. As sea-level rises, the thickness of the freshwater lens decreases, and hence the volume of fresh water decreases (Figure 6.3). Also sea-level rise would increase the likelihood of storm overwash of the islands, causing increased incidence of saltwater contamination of the freshwater lenses. Studies have also shown that as the atoll islands erode owing to increased sea-level rise and wave attack, a 20% reduction in the width of an island may cause a 50% loss of the volume of fresh water (Commonwealth Secretariat, 1989). Clearly, basic subsistence on these islands would be seriously impaired. If these changes are coupled with more frequently occurring droughts, the socioeconomic and ecological impacts could be devastating to these island countries.

Sea-level rise will impair estuarine water quality in other subtle ways, contributing to the degradation of in situ conditions for aquatic biota (eg increased temperature results in lower dissolved oxygen) and increasing the health risks of the population dependent on withdrawals of fresh water from the streams.

Increased precipitation and consequent riverine flooding, coupled with reduced interior drainage, could cause more frequent stormwater overloading of the municipal drainage and sewerage systems. The addition of large pulses of point source and non-point source pollution would contribute to general water quality degradation of riverine, estuarine and coastal waters. Less obvious are the potentially serious effects of the leaching of toxic and hazardous contaminants from countless hazardous waste sites, at least those in the US, that are located within the 100-year floodplain. Septic systems would fail and overflow more frequently as the soils remain waterlogged for extended periods. Moreover, if drainfields from septic tanks are less than 1.5 m above the watertable, they contaminate it; higher watertables would make this situation more commonplace. Finally, water bodies could stagnate, both because of higher temperatures and the decreased mixing and tidal flushing associated with deeper water (Park, 1990).

2.2.6' *Infrastructure*

Rising sea-level would expose coastal infrastructure to the combined impacts of waves, storm surges and erosion. In the US, about $100 billion could be required to protect tourist resorts and vulnerable urban areas from inundation and erosion alone. Modifications to stormwater and sewerage systems, ports and navigation channels, roads, bridges and water supply infrastructure could substantially increase this figure (Titus and Greene, 1989). Drainage improvements necessitated by a 1 m rise in sea-level for Miami International Airport alone, would cost about $US30 million (Miller, 1988). In Japan, the cost of modifying infrastructure for a 1 m rise in sea-level would be about $US20 billion (Mansfield and Nishioka, 1989).

Higher sea-levels would ease access to some shallow ports and through some sea-level canals.

2.3 Ecological impacts: alteration and degradation of the biophysical properties of beaches, coral reefs, estuaries and wetlands

2.3.1 *Wetlands*

Over two-thirds of fish caught for human consumption - as well as many birds and terrestrial animals depend on coastal marshes and swamps for part of their life cycles. Unlike most dry land, coastal wetlands can keep pace with a slow rate of sea-level rise. As Figure 6.4 shows, this ability has enabled the area of intertidal wetlands to increase several-fold with the slow rate of rise over the last few thousand years. However, if sea-level rises at a rate greater than the ability of wetlands to keep pace, the area of wetlands could decline by a similar amount; and when bulkheads and dikes protect adjacent dry land, there could be a complete loss (Titus et al., 1984; Titus, 1986, 1990).

Kana et al. (1988a and 1988b) surveyed the intertidal wetlands around Charleston, South Carolina, and Long Beach Island, NJ. In the Charleston site, they found that a 90 cm rise would inundate 50% of existing wetlands, although the net loss would be only 40% if wetlands are able to form inland. In the case of a 140 cm rise, they estimated that 90% of existing wetlands would be lost, but the net loss would be only 80% if the adjacent dryland areas are abandoned. In contrast, in the Long Beach Island site they found that a 90 cm rise would have little impact on total wetland acreage; the primary impact would be to convert the predominant high marsh to low marsh; a 140 cm rise, however, would drown 80% of the wetlands.

Park et al. (1986) used topographic maps to attain a first approximation of the impact of sea-level rise on US coastal wetlands. Their results suggested that a 1.4 m and 2.1 m rise in sea-level would inundate 47% and 80% (respectively) of US wetlands, but these losses could be reduced to 31% and 70% (respectively) if adjacent developed lowland were abandoned to the advancing sea.[1] However, Titus (1988) noted that interpolation of topographic maps inherently overestimates wetland elevations, and hence underestimates wetland loss. Therefore, Park et al. (1989) revised their regional study, this time using an unbiased procedure for estimating wetland elevations and using the lower estimate of a 1 m rise in sea-level. The revised results implied that such a rise would inundate 50-82% (95% confidence interval) of existing wetlands, but that the net loss would be reduced to 29-66% if only densely developed areas are protected.[2]

The applicability of these estimates for other countries is unknown. Because wetlands are found below the annual high tide, the most vulnerable areas would tend to be those in areas with small tidal ranges, such as the Mediterranean and Black seas,

1. These results are reported in Titus, 1988, who did regional weighting to obtain national results.
2. These results are reported in Titus and Greene, 1989.

the Gulf of Mexico and estuaries with narrow openings to the sea. The least vulnerable would be those in areas with large tidal ranges, such as the Bay of Fundy.

A recent global survey of coastal wetlands and mangrove swamps was conducted by the Netherlands (Rijkswaterstaat, 1990). This survey, which did not include data from the US, Canada, Australia and New Zealand, shows that, in the aggregate, there are about 730,000 km^2 of coastal wetlands, plus another 165,000 km^2 of mangroves. Eight countries out of 120 surveyed - Mexico, Brazil, Argentina, Cuba, Indonesia, Papua-New Guinea, Vietnam and Malaysia - possess slightly more than half of the world's coastal wetlands. They found through their survey that about 88% of the total coastal wetlands areas of the world are situated in regions with a population density of less than 10 inhabitants/km^2. They reason that these areas are unlikely to be protected by 'hard' coastal structures because of unfavourable economics, and thus, the land uses upland of the wetlands pose no barriers to the landward migration and transition of wetland types as sea-level rises. At most, 5-10% of wetlands by area would be lost to hard coastal structures with a rise of 1 m given the current level of coastal development. This conclusion is similar to that of Park et al. (1989). Thus, most wetland loss would be due to inundation, not coastal structures. Nevertheless, several authors have cautioned that current rates of coastal development could lead to much greater proportion of the coast being developed, with a corresponding increase in wetland loss due to structures preventing the inland migration of coastal ecosystems (Everett and Pastula, 1990; Titus, 1990).

Coastal areas place an added problem of the presence of hazardous waste sites, the flooding of which could have serious environmental consequences. In the US, about 1100 active hazardous waste sites, and possibly as many closed or abandoned sites, are located within areas that have a probability of flooding once every 100 years (Flynn et al., 1984). Increased flooding could exacerbate the problem of hazardous waste entering the environment.

2.3.2 Background: importance of wetlands

Coastal tidal wetlands are very important to the functioning of estuarine and near-shore ecosystems. In Europe and the US, a large proportion of coastal wetlands has been lost to development - and a relatively high percentage continues to be lost annually through a combination of subsidence and sediment starvation caused by dams and dikes that restrict natural sedimentation. About 18,000 square km^2 of coastal wetlands remain in the US (Office of Technology Assessment, 1984).

Wetlands are vital to the ecology and economy of coastal areas. Their biological productivity is equal to or exceeds that of any other natural or agricultural system, (Teal, 1962; Ryzkowski, 1984). Wetlands support resident and migratory birds, coastal animals which use them for habitats and forage, and they are vital to the well-being of many species of fish and shellfish. Over half the species of commercially important fish in the southeastern US use salt marshes as nursery grounds. The value of marshes as habitat for various life-cycle stages of countless species may be their most important function. Wetlands also serve as sinks for pollutants and provide a degree of protection from floods, storms and high tides. Based on these functions, marshes have an estimated present worth to society of as much as $US13,600/ha (Thurman, 1983).

Coastal wetlands and estuaries are important to many species. If sea-level rise is too rapid, natural succession of the coastal ecology would not take place and could lead to disruption in the life cycles of many species. In the near term, production of fisheries could rise as marshes flood, die and decompose, thus improving fisheries habitat in some cases and providing more nutrients. Additional nutrients would become available from leaching of soils and peat which would flood more frequently. This temporary increase in productivity appears to be happening now in the southeastern US where sea-level rise is compounded by land subsidence (Zimmerman et al., 1989). However, this temporary benefit for fisheries may be balanced by negative impacts on birds and other wildlife as the habitat area is decreased. In the longer term, by 2050 the overall impact on fisheries and wildlife will probably be negative.

For example, in coastal Louisiana, US, brackish marshes are deteriorating because of high rate of sea-level rise (due to subsidence) and saltwater intrusion. Recent increases in juvenile shrimp in the fishery may be the result of a short-term increase in nursery area due to increased tidal penetration into the marshes. If this is so, then the increasing trend of shrimp production may be reversed if wetland deterioration continues (Condrey, 1989).

2.3.3 Redistribution of wetlands

An accelerated rise in sea-level could result in a substantial redistribution of coastal wetlands types. Salt, brackish and fresh marshes as well as mangrove and other swamps would be successively lost to inundation and erosion; others would transform and adapt to the new hydrologic and hydraulic regime or would migrate inland through adjacent lowlands not impeded by protective structures. The value of these wetlands as habitat for wildlife could be impaired during the transitional period and their biodiversity may decrease (Davis, 1985). Sedimentation and peat formation have allowed many wetlands to keep pace with sea-level rise in the last few thousand years, which has enabled the area of wetlands to increase in most parts of the world, as illustrated in Figure 6.3. However, if the sea-level rises more rapidly than the wetland vertical accretion rate, there could be a corresponding net loss of wetlands. Kearney and Stevenson (1985) found that in some areas, any acceleration of sea-level rise would induce a net loss of wetlands; in contrast, Park et al. (1986, 1989) assumed that wetland accretion in most areas could keep pace with an acceleration of 1 or 2 mm per year. The literature provides no evidence, however, that wetlands could generally keep pace with a relative sea-level rise of 1 cm per year, which would be reached by the year 2100 even in the 50 cm scenario. In fact, such a rate would be as great as the rate attained during the disintegration of the continental ice sheets at the end of the Pleistocene, which drowned barrier islands and associated features on the continental shelves (Peltier, 1988).

Owing to the combination of climatic changes, it is expected that specific ecological communities within coastal ecosystems will not only move inland, wherever humankind does not intervene, but will generally move poleward.

2.3.4 Changes in nutrients and chemicals

Particularly for a large rise in sea-level, biogeochemical cycles will be altered by saltwater inundation of land not submerged in millennia. Increases in nitrogen and phosphorous concentrations can be expected as well as the release into the marine environment of pesticides and toxic substances resident in the ground.

2.3.5 Other ecological impacts of sea-level rise

There are several ecological impacts of sea-level rise beyond those in wetland areas. Many species of sea turdes are recognised throughout the world as threatened with extinction. (Everett and Pastula, 1990). As nesting beaches are lost, either by sea-level rise or by human development, additional significant stresses will be placed on turtle populations. In addition, dune ecosystems are also important to many species of birds and other animals as nesting and foraging areas.

Many marine mammals rely on beach zones for critical parts of their life cycle. Sea-level rise approaching the 1 m worst-case scenario may inundate some important haulout or put these mammals into conflict with human uses; however, in most cases animals are expected to adapt. On the other hand coral reef communities have a limited capacity to adjust to sea-level rise: whereas the corals appear to have accommodated to historic sea-level change rates, it is unclear whether they can adjust as readily under rates approaching the worst-case scenario.

In addition, a rapid rate of sea-level rise may threaten coral reefs which fringe coral atolls and provide the material sustenance for them. They may not be able to keep up with the sea-level rise, thus causing their ecological structure to change as they become flooded.

2.4 Physical aspects of shoreline retreat: inundation, erosion and recession of barrier islands, coral reefs and other shorelines

2.4.1 Background

The primary direct physical effect of sea-level rise is inundation. Inundation increases the rate of shoreline recession or retreat by raising the mean water level upon which the tides, waves and storm surges can attack the beaches, bluffs, embayments and barrier islands of the world's coastlines. Historically, submergence has accounted for a relatively small portion of net shoreline recession along exposed sedimentary coasts (Hands, 1976). That is, most sandy shorelines worldwide have retreated during the past century because of the erosion associated with the regional storm and wave climate (Bird, 1976). Locally, human interference with the coastal sediment transport regime has accelerated erosion problems, as jetties and groins have impeded littoral transport processes. On a global scale, however, human interference cannot be considered a primary cause of erosion since retreat also occurs on sparsely populated and little-developed sandy coasts (Bird, 1976). Less than 10% of the length of the world's sandy shoreline has progressed, more than 60% has regressed, and the balance (30%) has been relatively stable or has shown no consistent trend during the past century (Bird, 1976).

The slope of the beach foreshore is the controlling variable of shoreline recession: steep-sloped shorelines will experience relatively little horizontal displacement with each increment of sea-level rise. Gently sloping shores will undergo much greater recession and flooding for the same increment of sea-level rise (National Research Council, 1987).

For example, the deltaic coast of Louisiana in the Gulf Coast region of the US has been receding at a rate of 4.2 m/yr (May et al., 1983). This is associated with a relative rise of sea-level (caused mostly by subsidence) of about 1 cm/yr. Along sand beaches, the general rule of thumb for the relationship of average beach recession to sea-level rise is about 100:1, ie a shoreline recession of 100 m for a 1 m rise in sea-level (National Research Council, 1987).

It is essential to understand the effects of sea-level rise on coastal physical processes, for these processes will not only determine the overall physiographic and geomorphological features of the coast, but also their interaction with man-made structures designed to stabilise the shoreline. Our ability to predict these processes under contemporary slow rising sea-level remains rudimentary, even though a considerable amount of empirical and theoretical coastal engineering research has been accomplished (National Research Council, 1987).

2.4.2 Global projections of inundation and recession

The recent Dutch study (Delft Hydraulics Laboratory, 1990b), estimated the total shoreline length that would be inundated or otherwise affected by a rise in sea-level of 1 m. Low coasts were defined as those with a coastal zone broader than 25 km below the 100 m contour. In addition, the Dutch reasoned that only coastal areas with a population density greater than 10 inhabitants/km^2 could be considered vulnerable to the combined threat of inundation, flooding and erosion. Over 345,000 km of low coast in 181 countries were identified and surveyed on the basis of these assumptions, along with 10,700 km of barrier island beaches and major recreational oceanic beaches. The Dutch used Leatherman's (1988) estimates for the length of sandy shorelines in the US. Of the 11,000 km of sandy shoreline in the US, some 3000 km were considered to require some form of stabilisation.

According to the US Army Corps of Engineers' National Shoreline Study (1971), there are approximately 51,000 km of shoreline in the conterminous US (excludes Alaska which has about 75,000 km and Hawaii). Of the 51,000 km, about 24,500 km (nearly 50%) were considered erosional, but only 3000 km were considered to be critical enough for protective action. Currently, only about 1000 km are protected by some form of 'soft' (eg periodic beach nourishment) or 'hard' structural measures. These figures are presented as a rough indicator of the current degree of protection that is considered economically feasible for a country.

2.4.3 Shoreline erosion and stabilisation

As was demonstrated by the Dutch worldwide survey of coastal inundation, low coasts of variable sedimentary composition and morphology dominate the statistics. They consist of sandy, rocky or muddy substrates, supporting various types of vegetation such as marshes, mangroves and meadows. Erosion processes are variable and as a result are difficult to predict. Apart from direct inundation, and the impacts on human safety and agricultural productivity, there is the perpetual issue of barrier island stabilisation from the erosive forces of wind, waves and storm surges.

Because of human habitation on inherently hazardous shores, primarily for recreation and aesthetic enjoyment, society has taken actions to stabilise these highly mobile shores through various protective measures that include periodic beach nourishment, groins, breakwaters, bulkheads and riprap. One of the most important aspects of shoreline management is the stabilisation of inlets and navigation channels that are needed for recreational boats as well as for commercial navigation, including fishing fleets.

Barrier islands and classical sandy coast-lines apparently account for a very small proportion of the total shoreline subject to inundation due to projected sea-level rise according to the Dutch survey. Much of the research and literature on shoreline stabilisation issues deal with the highly mobile, dynamic processes associated with these beaches. There is still considerable debate in the literature regarding the origin and fate of barrier beaches under conditions of sea-level rise. The general consensus is that in response to sea-level rise, barrier islands tend to migrate landward as storms wash sand from the ocean side to the bay side. This overwash process may enable barrier islands to keep pace with an accelerated sea-level rise (Leatherman, 1982). However, there is also a belief that these barrier islands will either disintegrate or will merge with the mainland, if the rate of sea-level rise is rapid.

The lagoons and embayments behind barrier islands and spits provide natural sheltered harbour. In their natural conditions, the tidal inlets between barrier islands migrate along the shoreline, whereas when stabilised by jetties, they are fixed in position to provide the essential and reliable navigation channels (National Research Council, 1987). In some bays and inlets, the tidal transport of sediment creates shallow delta, depositing the sediment load either on the seaward side of the bay entrance (on the ebb-tide) or on the bay side (on the floodtide). Consequently, as sea-level rises, the volume of these shoals will increase correspondingly, and the elevation of these deltas will grow in elevation to keep up with the rising sea-level.

The shoreline stabilisation implications for the downdrift beaches are clear. Ebbtide deltas will become ever greater barriers to downdrift longshore transport of sediment, causing greater erosion downstream of the inlets. Unless there are sand bypass technologies available, the rate of erosion would be greater than that expected by sea-level rise (National Research Council, 1987).

The costs of navigation channel and tidal inlet maintenance, through dredging, sand bypassing, and construction ofjetties, will increase at a greater than linear rate. This is because some of the sediments are polluted and the costs of dredged material disposal have increased sharply over the past decade as a result of a variety of stringent environment regulations in many developed countries.

2.4.4 Examples of sea-level rise impacts on particular regions

The Mediterranean The Mediterranean region has about 46,000 km of coastline, 75% of which is found in four countries - Greece, Yugoslavia, Italy and Turkey (Telegersma and Sestini, 1989). More than 50% of the coast is rocky, the rest being considered sedimentary (Baric, 1989). Tourism comprises a large part of the economy of these countries: over 100 million visitors annually in 1984. Tourism associated with beaches and recreational navigation would be most adversely affected in the European Mediterranean, because many of the beaches are small pockets fringed by rocky coastlines.

Venice, Italy Since 1890, relative mean sea-level in Venice has risen by about 25 cm. The mean number of floodings has increased over that period from 10/yr to 40/yr (Sbavaglia et al., 1989). In terms of damaging effects, the increased flooding is equivalent to increasing the frequency of 'normal' floods, as well as that of rare floods, although no statistical evidence has shown that the frequency of storms has increased. Further rises in sea-level will only exacerbate the problem.

Egypt A i m rise in sea-level would extend inland over 30 km south of the city of Alexandria, which is a highly industrialised city. Furthermore, erosion and accretion patterns along the Mediterranean coast of Egypt would change significantly, affecting the important tourist, recreational and economically developed areas (El Raey, 1989).

Poland Poland has a 493 km long coast on the Baltic sea, which consists of alternating cliffed (105 km) and barrier beaches (373 km). The coast is relatively low lying. Almost 3000 km^2 lies below an elevation of +2 m (mean sea-level), with a total population of 405,000 in this low-lying zone that would be seriously threatened by a 1 m rise in sea-level (Rotnicki and Borowka, 1989). The recession rate is estimated to be 2.3 m/year.

In the Odra River valley, a sea-level rise of 0.5 m will have a direct impact on a floodplain 3-4 km wide and extending 50 km upstream, and a corresponding increase in the salinity of surface and groundwater. (Rotnicki and Borowka, 1989).

Ivory Coast The Ivory Coast has 550 km of low barrier beach shoreline which is fringed with 350 km of lagoon covering about 1200 km^2. Approximately 3 million people out of a total population of 10 million live along the coast and derive their livelihood there. A large portion of the sandy shorelines is being eroded at a rate of 1-2 m/year (Kaba et al., 1989). Increased sea-level will accelerate the shoreline recession rate.

Ghana The Ghanaian coastline stretches for approximately 550 km and suffers from severe erosion, which would be accelerated by sea-level rise. Many towns and villages have been retreating from the large rate of coastal recession. Flooding has been a major problem for many of the villages, disrupting daily life and the means of subsistence which is dependent on agriculture and fisheries.

Argentina The Argentine coasts exhibit a diversity of coastal geomorphic features, with different tidal and wave regimes. Of the 5000 km of coastline, especially severe erosion occurs in the Province of Buenos Aires, with a coastline of 1800 km and 40% of the country's population. Coastal floods are severe on the shores of the Rio de la Plata. Coastal recession in some sections of the shore exceed 5 m/yr (Schnack et al., 1989) and is expected to continue.

Guiana Coast, South America The Guiana coast (Guyana, Surinam and French Guiana) can be designated as a low-lying chenier plain, much of which would be inundated by a sea-level rise of 30 cm. More than 90% of the population of the Guiana coast lives in the coastal plain. A i m rise in sea-level would cause the coastline to retreat 2-5 km, causing large-scale disruption in urban and agricultural areas (Daniel, 1989).

Australia Australia's coastline is dominated by sedimentary deposits composed of sand (16,000 km^2)

and mud (6500 km^2). In addition, there are hundreds of deltas, bays, estuaries and offshore islands that would be vulnerable to rising sea-levels (Prime Minister's Science Council, 1989). Australia's Great Barrier Reef and the reef complexes of western Australia are active coral communities which could be threatened by the rate of sea-level rise in the high scenario.

China A i m rise would flood or destroy most salterns and seawater breeding farms. Reconstruction will require 5000 km^2 of land. Nearly half of the Pearl River Delta would be inundated, along with the more developed areas of the Yangtze and Yellow Rivers. There will also be other widespread impacts on housing, transport, and food and water supply (Ruqiu, 1990).

Soviet Union The Soviet Union is a nation with a great diversity of coasts and there are varying directions and amounts of vertical movement of local land masses. Thus, even though the overall amount of change for the nation is an increase of 1-2 mm per year (similar to that observed for the world), the local impacts will vary considerably. This is particularly so because there are periodic changes in sea-level of 5, 7, 10, 12, 20 and 22 years for different areas of the Soviet Union, thus compounding the impacts on areas that are in a natural period of increasing sea-level (Goskomgidromet, 1990).

3 The ecological and socioeconomic impacts of climate change on the world ocean

3.1 Introduction

The earth's climate is directly influenced by the ocean-atmosphere system. The two continuously interact. The World Ocean plays a deciding role in the turnover of water and CO_2 as well as in the biogeochemical cycling of all the most important biogenic elements.

Because of this, the predicted global climate warming (for the middle of the next century) will have an appreciable effect on the state of the World Ocean and, consequently, on the nature of its effects on human kind. The magnitude and direction of such an effect may differ significantly between the open ocean and coastal zones. Possible physiochemical, ecological and socioeconomic consequences will be determined by the specific character of the function of marine ecosystems, their regional peculiarities and their role in the world and national economies.

A whole complex of scientific methods and approaches is necessary to assess the impact of global climate warming on the World Ocean. Data from the GCMs of the coupled ocean-atmosphere system, and the global CO_2 cycle, results of palaeooceanographic investigations, analog comparisons, analysis of ecological observations and economic estimates were used in this report.

An analysis was conducted of possible changes in the physiochemical parameters of the ocean environment and their influence on the biological and ecological characteristics of marine ecosystems on global and regional scales.

Socioeconomic consequences were assessed on the basis of the expected changes in the state of fisheries in the open ocean and coastal zones using historic analogs.

As a whole, comprehensive assessment of the effect of global warming of the World Ocean and its coastal zones will contribute to forecasting the development of human civilisation in new climatic conditions, as well as planning the system of adaptive options.

3.2 Impact on physiochemical processes

3.2.1 Impact of global warming on the heat budget and water circulation of the World Ocean

A key problem in forecasting possible changes in all fundamental natural processes under changed climatic conditions is assessing the impact of global warming on the heat budget and water circulation of the World Ocean. Because changes in the composition and circulation of the atmosphere affect the processes occurring in the ocean and, vice versa, it is necessary to consider the function of the ocean-atmosphere system in conditions of the development of the greenhouse effect to resolve this problem.

One of the most promising methods to investigate the sensitivity of the climatic system to the gaseous composition of the atmosphere is the performance of numerical experiments with the use of the numerical GCMs of the coupled ocean/atmosphere system (Manabe and Stouffer, 1980; Schlesinger, 1986). Using these models, it is possible to predict a change in the temperature regime of the lower atmosphere and the surface layer of the oceans.

Among the coupled ocean-atmosphere GCMs, those of the Oregon State University (US) (Ghan, 1982; Schlesinger and Mitchell, 1987), the Goddard Institute for Space Studies (US) (Hansen et al., 1983, 1988), the Geophysical Fluid Dynamics Laboratory of NOAA (Princeton, US) (Manabe and Wetherald, 1980, 1987) and the National Center for Atmospheric Research (US) (Washington and Meehl, 1989) include most of the principal factors influencing the coupled circulation processes.

The basic parameters studied in all these models are: sea surface temperature, average surface wind speed, solar radiation flux, total cloudiness, sea-level pressure and evaporation. In each model, the ocean is considered as a simple mixed layer; ice cover and its melting are also included. However, none of the published coupled ocean-atmosphere GCMs has a satisfactory treatment of sea ice or deep ocean circulation. A chronic problem in these models has been a too large ice extent and too weak thermohaline circulation in the northern North Atlantic and its connection to the Arctic Ocean (Bryan, 1986; Washington and Meehl, 1989). In their present state of development, the global climate models are unable to capture some of the possible feedbacks that may occur in the ice-ocean system as a response to atmospheric warming.

Results of numerical experiments with these GCMs show a good qualitative agreement in the basic trends for thermal budgets of ocean and atmosphere under conditions of doubled atmospheric CO_2. However, significant differences exist in the quantitative estimates. According to these calculations, the warming of the lower atmosphere by 1.3°-4.2°C should be expected, with a more intensive warming on the land than on the ocean. Comparable sea surface temperature increases will vary from 0.2° to 2.5°C. Increased precipitation should also be expected, especially on the eastern edges of the continents. Analysis of the seasonal dynamics of the temperature field for all four models has pointed to the maximum warming occurring in winter in arctic and antarctic regions.

The predicted warming trend in arctic and subarctic regions is significant. An intensive warming in polar latitudes will reduce the meridional (north, south) gradients of sea surface temperature and, consequently, will lead to a decrease in the trade wind intensity and in the power of ocean currents (Mitchell, 1988). This, in turn, could lead to a reduction in the area and intensity of ocean upwelling, such as in the equatorial eastern tropical Pacific.

On the other hand, GCMs predict that increases in temperature gradients between the strongly heated land mass and the cooler ocean can drive a competing mechanism by intensifying the along-shore wind stress on the ocean surface. This process would be accompanied by acceleration of coastal upwelling This is confirmed by present-day natural observations of upwelling dynamics (Bakun, 1990). These data from widely separated areas of the world suggest that the equator-ward along-shore wind stress has been increasing during the respective upwelling seasons of the past 40 years.

It is likely that both upwelling mechanisms could take place under conditions of global warming, but the dominance of one or the other mechanisms will be determined by the proximity to land (eg eastern boundary current regimes) or the open ocean (eg the North Pacific Equatorial Counter-current). Upwelling is likely to intensify in coastal regions, whereas oceanic upwelling may weaken. These subtle, but large-scale, changes have profound impacts upon the fisheries as well as on the climate of the immediate coastal zone.

Apart from the impact on the water circulation in the World Ocean, a warming in arctic and antarctic regions may have a significant influence on the state of the earth's cryosphere (glaciers and shelf and sea ice). Such changes will in turn further affect the global climate. First, sea ice, covering 11% of the world's ocean surface, affects internal ocean and ocean-atmosphere thermal exchange. These factors determine the intensity of convection in the ocean which characterises the mean time scale of processes occurring in deep ocean layers (for example, CO_2 uptake). Therefore, changes in the extent of sea ice will have an effect on atmospheric circulation and temperature. Also, open ocean waters absorb much more solar radiation than do those which are ice covered (Walsh, 1983). Second, even small changes in the earth's cryosphere could lead to a noticeable deviation of global sea-level from its recent average value. The predicted warming for the Arctic will lead to significant reduction in sea-ice extent around Svalbard, and along the north Siberian and Canadian arctic coasts. At the same time the projected rise in temperature for the period up to the middle of the 21st century is not expected to lead to a significant decrease in the amount of ice volume in the massive ice caps of Greenland and Antarctica. In fact, a recent study in the Northern Hemisphere has shown that despite a small increase in mean annual temperature, the extent of ice has increased in the most recent decade (Bryan et al., 1988). The predicted rise of temperature by 4°-5°C by the middle of the 21st century (Mitchell, 1988) might lead to acceleration of the ice flow from the continent into the ocean in west Antarctica and lead to decrease in ice cover in the Arctic (Budyko and Izrael, 1987). Owing to melting sea ice in the Arctic, freshening of surface waters in the North Atlantic would occur, interfering with bottom water formation. This process might affect the northward heat flux and cross-equatorial heat transfer (the so-called 'conveyor belt' (Broecker et al., 1985)), which could cause a shift in global ocean circulation (Broecker and Peng, 1990; Bryan, 1986). The consequences of such major changes in ocean circulation would be enormous in terms of regional climate and biochemical cycling. A major international program, the World Ocean Circulation Experiment (WOCE), is now under way to study this question.

3.2.2 Changes in the carbon cycle

The predicted increase of CO_2 in the atmosphere by the middle of the next century could lead to disturbances in the global carbon cycle and, as a consequence, could have strong feedback to the earth's climate system. To assess the impact of such an anthropogenic increase of CO_2 in the atmosphere and of resultant changes in the global carbon cycling on the World Ocean, it is necessary to improve our understanding of the cause-and-effect relationship of past natural CO_2 variations.

Measurements of gases trapped in polar ice cores (Barnola et al., 1987) convincingly demonstrated that the concentration of atmospheric CO_2 was subject to several dramatic natural changes which paralleled and possibly slightly preceded the major climatic fluctuations. Since the ocean contains about 60 atmospheric carbon units (Sundquist and Broecker, 1985) such changes, to a great extent, must be tied to the ocean. The 'biological pump' transfers CO_2 across the thermocline into deep water via photosynthetic marine organisms which incorporate gaseous CO_2 into carbonaceous compounds. The combined variations in the 'biological pump' process and in the chemistry and physical circulations of the ocean, could provide the dominant forcing of the observed changes in atmospheric CO_2 (Siegenthaler and Wenk, 1984). In this context, numerous models have been proposed and examined (Sundquist and Broecker, 1985; Meir-Reimer and Hasselmann, 1987; Mix, 1989).

One important result of such model experiments, using data from ocean palaeoproductivity estimates, is that changes in coastal and equatorial upwelling may in part control atmospheric CO_2 (Sarntheim et al., 1988; Flohn, 1982). Recent studies have shown that this factor alone cannot explain the whole amplitude of natural variations and that a major role for controlling atmospheric CO_2 levels is played by the ocean alkalinity which determines the solubility of CO_2 in ocean water. Alkalinity variations appear to be triggered by changes in deep water formation in the high-latitude North Atlantic (Boyle, 1988; Broecker and Peng, 1990).

According to Takahashi's estimates of CO_2 source/sink regions in the World Ocean (Takahashi, 1989) the most intense source of CO_2 is the equatorial Pacific and the most intense sink is the subantarctic belt, 40°-55° S. Coastal and equatorial upwelling regions are carbon sinks because of their productivity, but are net sources of CO_2 due to outgassing of CO_2-enriched waters, which overpowers the carbon transfer by productivity.

Furthermore, increased dissolution of carbonates due to the acidification of sea water by an increase of CO_2 would lead to higher alkalinity and therefore higher CO_2 uptake capacity of the ocean (Boyle, 1988). Enhanced burial of organic matter in ocean sediments due to increased nutrients influx would promote the sequestering of CO_2 from the atmosphere (Siegenthaler, 1989). Lastly, arctic/subarctic seas are also significant sink areas for anthropogenic CO_2 (Roots, 1989).

Expected changes in the carbonate system and in the transport of particulate organic carbon from surface into deep ocean layers will greatly affect the marine biota. For example, recent results have suggested that the dissolution rate of shells of some mussels may be significantly higher than hitherto assumed (Betzer et al., 1984).

In conclusion it should be noted that increasing CO_2 in the atmosphere could lead to disturbances in the global carbon cycling. The direction and magnitude of such changes will be determined to some extent by the functioning of upwelling ecosystems and changes in oceanic carbonate systems under the conditions of global warming.

A major international program, the Joint Global Ocean Flux Study (JGOFS) has been set up under the auspices of the ICSU-sponsored Scientific Committee on Oceanic Research (SCOR) for the decade 1990-99. Its main purpose is to investigate the flux of carbon in the ocean and the extent to which the oceans may affect climate change by exchanging CO_2 with the atmosphere.

3.2.3 Changes in nutrients

In highly industrialised regions, such as the North Atlantic community, increased discharge of anthropogenic gases and aerosols containing compounds of nitrogen, phosporous and sulphur into the atmosphere, results in increased fluxes of these substances from the atmosphere into the ocean (Oppenheimer, 1989). This process could be of great importance for nitrogen and sulphur, the atmospheric inputs of which to the photic zone of the ocean (at least for the Sargasso Sea and the equatorial Pacific) are comparable to diffusive convectional inputs (Duce, 1986). Marine biota may respond to these changes in nitrogen and sulphur contents with increased productivity, especially in impacted areas of the ocean. Such processes are already observed in the North Sea (Lancelot et al., 1987).

Sea-level rise, followed by flooding and erosion of soil, could lead to substantial increases in the flow of nitrogen, phosphorous and sulphur into the coastal zones, creating the potential for severe eutrophication. The consequence will be an acceleration of biochemical cycling of all biogenic elements (Oppenheimer, 1989). In turn, the increased cycling could cause a rise in the productivity of adjacent nutrient-poor ecosystems, particularly the so-called 'oceanic deserts'. However, whether or not nutrient supplies and productivity would actually increase as a result of increased wetland and sediment erosion from sea-level rise appears to be dependent on regional conditions. For example, in the Beaufort Sea, eroding peat from the tundra may be an important source of organic carbon for the coastal food chain, but in warmer water, such as the gulf of Mexico, where the biodegration and nutrient recycling rates are higher, the eroding nutrient and organics may not provide a significant contribution to the overall flux of materials. Rather, the relationship of increased fishery yield with wetland degradation in warmer waters may be more plausibly related to increased wetland-saltwater interface, affecting habitat dimensions (Condrey, 1989). This phenomenon has been observed, at least for the short term, in the Gulf of Mexico (Zimmerman et al., 1989). Oxygen depletion also occurs in association with increased eutrophication, especially in estuarine and deltaic regions adversely impacting all higher life forms.

If, as suggested by GCMs, some mid-latitude continental areas will become more arid, then fewer nutrients would flow through river systems to estuarine areas (Glantz, 1989) although the reduction in nutrient may not be proportional to reduction in precipitation and river discharge. Loss of nutrients could have an adverse effect on fish populations and decreased river discharge would affect some organisms which depend on fresh discharges for spawning. River systems of this type might include the Mississippi (US) and the Nile (Egypt) (Condrey, 1989,). On the other hand, precipitation and runoff are expected to increase in'most high-latitude continental areas, thereby increasing the volume of nutrients delivered to subpolar continental shelf areas.

The reduction or displacement of salt marshes and littoral zones as a result of sea-level rise could lead to a sustained loss or disturbances of habitats of marine plants which synthesise dimethylsulphide (DMS) (Holligan and Kirst, 1989). DMS is the most important component of the global sulphur cycles and could be a major source of cloud condensation nuclei over the oceans (Charlson et al., 1987; Griffin, 1988) with consequent influences on global albedo and climate.

The subgroup takes note of the discussions on the feasibility of fertilising the oceans with iron which would be carried to appropriate iron-deficient zones by vessels. The idea is to increase primary production, leading to removal of some CO_2 from the atmosphere and is based on the work of Martin (1990). We urge full consideration of ecosystem impacts and strong caution in these discussions.

3.2.4 Changes in contaminants

A rise of temperature will result in the acceleration of biodégradation of global organic pollutants (petroleum and chlorinated hydrocarbons etc). This process would promote their removal from the photic zone of the ocean (Izrael et al., 1990; Tanabe, 1985) On the other hand, sorption of these compounds on suspended matter may decrease as a result of higher temperature, which will lead to less deposition of these pollutants in the bottom sediments (Pierce et al., 1974). As a consequence, it could increase the 'residence time' of the pollutants in ecosystems.

The increase of UV-B radiation intensity (as a result of depletion of the atmospheric ozone layer) will increase the intensity of photochemical processes, particularly at the air/sea interface (Zika, 1989). This factor would accelerate the photo-destruction of polychlorinated biphenyls (PCB) and polyaromatic hydrocarbons (PAH) and, as a consequence, reduce this type of pollution in sea water (Doskey and Andren, 1987). But at the same time, increased penetration of solar UV-B radiation itself can have widespread adverse effects on life in the open ocean and wetlands. (US EPA, 1987).

The increased concentration of atmospheric CO_2 could probably cause some acidification of surface waters (Wilson and Mitchell, 1987). The process will not influence the behaviour of organic hydrophobic contaminants, but it could be rather significant for ionogenic compounds. The assciated decline in pH could enable the enhanced penetration of organic ionogenic compounds through cell membranes and, correspondingly, the increased accumulation of pollutants in hydrobionts (Landner, 1989). Furthermore, the enhanced acidity may decrease the stability of the complexes of heavy metals with humic substances (Paxeus, 1985; Mantoura and

Riley, 1975). The process may be accompanied by an increased toxic impact on marine organisms (Sunda and Lewis, 1978; Sedlacek et al., 1983).

3.3 Ecological impacts

Physical-chemical parameters are the primary determinants of the distribution of marine habitats, communities, and ecosystems. A change in these parameters (described above) will have broad impacts on basic ecological structures and processes. These changes will, in turn, cause impacts on marine and coastal resources.

3.3.1 Changes in habitats

The predicted temperature rise of surface waters and a change in the ocean circulation would substantially impact on the structure and location of marine habitats. However, marine organisms, as a rule, have rather high genetic and behavioural plasticity, allowing them to adapt to constantly changing environmental conditions. This property is a basis for the relative stability of zoogeographical patterns under the conditions of natural climate variations (Odum, 1986).

Under the present scenario for anthropogenically-influenced climate change, a general global warming is postulated, causing poleward spreading and deepening of warm oceanic waters. The response of biological communities will, in general, reflect poleward translocation to new optimal habitat. However, some life forms that are relatively immobile or are genetically less adaptable may be threatened with extinction if the rates in the worst-case scenario are realised (Sharp, 1989).

Global warming could have especially strong impacts on the regions of sub-polar fronts (Roots, 1989) where the temperature increase in deep water could lead to a substantial redistribution of both pelagic and benthic communities, including commercially important fish species. At the same time, a similar temperature rise in tropical latitudes would not affect greatly the functioning of marine organisms.

However, the distribution of biological populations, as well as their abundance, appears often to be more related to the dynamic physical processes that control various patterns in the ecosystem than to the direct effects of temperature itself (Bakun, 1990). For example, recent empirical results (Cury and Roy, 1989) indicate that reproductive success of pelagic fishes in upwelling regions mostly depends on wind stress.

As a result of changes in the ocean and coastal zone, there may be impacts on biodiversity. In the open ocean, the effects on biodiversity will likely be less than those expected in the estuaries and wetlands. The oceanic ecosystems will be relatively free to move to new geographic areas while the near-shore ecosystems are more constrained by the physical features of the shore. With regard to the coastal ocean, the effects of changing freshwater inputs as a result of changing precipitation patterns, and the consequent impact on estuarine habitats, circulation, and nutrient and sediment supply warrant consideration. It is important to keep in mind the dynamics of shelf-water masses are influenced by meteorological forcing in addition to upwelling, as classically defined. In warm temperate and sub-tropical regions (eg the southeast US and Gulf of Mexico) cross-shelf transport, associated with frontal passages, is important to the transport offshore of eggs and larvae of estuarine-dependent species of fish and crustaceans. Thus, meteorological forcing influences shelf-water mass stability and advection, which in turn has important biological and geochemical consequences.

In summary, global warming may cause considerable changes in the structure and distribution of marine habitats, thereby greatly impacting on the structure and operation of world fisheries.

3.3.2 Changes in production/destruction processes and biosedimentation

To assess possible consequences of the effect of global warming on the productivity of oceanic ecosystems, it should be taken into account that 45% of the annual primary production of organic matter in the World Ocean is synthesised in the upwelling zones and high-latitude regions, and 20% is in near-shore waters (Koblents-Mishke et al., 1970; Sarnthein et al., 1988). Hence, the productivity of the global ocean in the new climatic conditions would be first of all determined by the changes in functioning of the ecosystems of those highly productive regions.

Current forecasts of the possible changes in ocean productivity are mainly based on the outputs of GCMs and the result of palaeoclimatic reconstructions.

GCM outputs indicate that climate warming causes a decrease in meridional temperature gradients (Schlesinger, 1986; Mitchell, 1988), as well as a general weakening of oceanic upwelling. Numerous palaeoclimate studies have estimated past productivity that tends to confirm the GCM results. According to these studies, the productivity of oceanic upwelling regions during glacial periods was much higher than during interglacial periods (Sarntheim et al., 1987; Sarntheim et al., 1989; Lapenis et al., 1990). All of these studies indicate that global warming should be accompanied by a fall of productivity in upwelling regions and, thus, a decrease in total productivity of the global ocean (Budyko and Izrael, 1987; Lapenis et al., 1990).

The mechanisms just discussed deal primarily with the open reaches of the global ocean. However, as previously noted in Section 3.2.2, the predicted intensification of the coastal upwellings would tend to enhance primary organic production in these systems. But whether this increased primary production would be channelled to trophic components that society particularly values is unclear. There has been little clear demonstration that increased primary production actually promotes reproductive success and population growth of commercial fishes. (Bakun, 1990). Consequently, conclusions about compensatory changes in total ocean productivity under the present scenario cannot be made on existing information.

Apart from tropical and mid-latitude regions where productivity is mainly determined only by the contents of nutrients, the basic limiting factors in polar and subpolar regions are light and temperature. A rise of mean temperature of high latitudes will lead to an increase in the duration of the growing period and ultimately in the bioproductivity of these regions.

However, the predicted rise of water temperature will be accompanied by an increase in the rate of degradation of organic matter, especially in subpolar waters as well as in shelf waters and the surface layer of the boreal zones by 1.1 to 1.3 times (Odum, 1986; Izrael and Tsyban, 1989).

Biodégradation rates in the surface layers in low latitudes are determined by the inflow of organic matter from sub-polar regions through meridional transport of intermediate and deep waters. In this connection, elevated temperatures are expected to increase biodégradation rates. However, the overall amount of low-latitude biodégradation may not be changed significantly.

According to Suess (1980) the amount and the rate of biosedimental flux would increase with an increase in productivity. So, taking into consideration the predicted changes in production/destruction processes the enhanced biosedimental flux is expected in the coastal upwelling zone (Bakun, 1990). At the same time, increased production in subpolar regions does not appear to be accompanied by raising of the biosedimental flux due to intensive microbial degradation.

Increased anthropogenic pollution in the global oceans is expected to affect the rate of production of organic matter. According to the estimates, the quantity of the contaminants in the photic zone of the ocean would have increased by 25-30% by the middle of the next century (Izrael and Tsyban, 1989). Besides, the warming of the sea water followed by the acceleration of chemical reactions could lead to the strengthening of toxicity of the contaminants to marine biota. This process would negatively affect the productivity of oceanic ecosystems (Tsyban et al., 1985; Patin 1979).

In conclusion, it should be noted that primary production does not necessarily equate with fishery production. Nevertheless, under conditions of global warming, changes in the centres of primary production could lead to changes in the distribution patterns of commercially important fish stocks and the recruitment of fish resources.

3.3.3 The role of ice in supporting polar ecosystems

Ice plays a major role in the development and sustenance of arctic and subarctic ecosystems: (i) it plays a significant role in the growth of marine algae (the primary source of food for the marine ecosystem), (ii) it creates a productive environment at the ice/water interface, allowing plants to grow and, in turn, supporting abundant and diverse communities, and (iii) it supports organisms which form a link in the transfer of energy between primary production (algae and phytoplankton) and fish, sea birds and mammals.

One of the possible consequences of global warming would be to reduce the extent and persistence of sea ice, affecting the production regimes and ecosystems accordingly. For example, the absence of summer ice over the continental shelves of the Arctic Ocean would radically increase the productivity of affected areas, given an adequate supply of nutrients.

Polar mammals use ice in particular ways to support their feeding and reproduction needs. For example, the range of polar bears is determined by the maximum seasonal extent of sea ice in any one year and clearly, without ice, the very existence of polar bears and also some seals would be threatened. Similarly, a reduction in ice would be expected to have a significant effect upon the feeding, breeding and resting activity of penguins and walruses and they would be very vulnerable to hunting and predatory pressures. If ice is reduced, other animals, such as the otter, would move into new territories. It is not clear how the migratory patterns of animals, such as whales which follow the ice edge, would be affected by changes in ice distribution.

Changes to water temperature and wind regimes as a result of global warming would also probably affect the distribution and characteristics of polynyas (ice-free areas) which are so vital to the polar ecosystems. Also, changes in the extent and duration of ice, combined with changes in characteristics of currents, for example the Circumpolar Current in southern latitudes, may affect distribution, mass and harvesting of krill. Krill is an important link in the food chain of southern ocean fauna and an economically important fishery. It is important to understand how and where the Southern Ocean productivity will change under global warming processes.

3.3.4 Regional aspects of the problem (the Bering Sea as an example)

It is predicted that high latitudes would be profoundly influenced by global warming (Roots, 1989). There could be marked changes in the functioning of sea ecosystems. Thus, it is necessary to summarise the results of modern ecological observations of the state of sub-polar and polar ecosystems with the aim of having an earlier understanding of the effects of global warming.

The Soviet-American long-term research study (Programme 'Bering Sea', Project 'Comprehensive Analysis of the Environment') has produced a large amount of information about the functioning of the subarctic ecosystem of the Bering Sea.

Under conditions of global warming in the region of the Bering Sea, according to the predictions of GCMs, the shift of the sea surface isotherms towards the North Pole could occur (warming by 0.5°C for a decade could be followed by the shift of more than 50 km) (Hansen et al., 1988). Such a temperature shift would lead to an increase in the area and duration of the ice-free season, which would in turn increase the growing season (Roots, 1989), thereby further enhancing the productivity of the Bering Sea ecosystem.

According to current estimates, the mean value of primary production in the Bering Sea is 0.65 g C/m^2 per day reaching in some areas 7 g C/m^2 per day, (Izrael et al., 1986; Whitledge et al., 1988; McRoy and Goering, 1976). With the expected creation of more favourable conditions for marine biota, the mean value of primary production could rise to 0.75-0.90 g/Cm^2 per day.

Taking into account that, at present, the mean value of the microbial degradation of organic substances in the Bering Sea is 0.3 g C/m^3 per year (Izrael et al., 1986; Whitledge et al., 1988), the predicted intensification of these processes under conditions of global warming in subpolar regions could lead to raising the magnitude up to 0.35-0.50 g C/m^3 per year.

The expected acceleration of the microbial and photochemical processes, followed by the increase of the destruction of organic contaminants, could cause some decrease of the anthropogenic pollution of the ecosystem (Izrael et al., 1990).

The acceleration of the production/degradation processes would lead to the intensification of the biogenic sedimentation. Also, some increase in biosedimental flux would be possible. It is estimated that 1.6 x $10^8$1 C per year is deposited in sediments of the Bering Sea (Izrael et al., 1986). This could be taken as a minimum one of the carbon flux fiom atmosphere to the seawater, since 53 x 10^8 t C per year is estimated as the general flux of carbon from the atmosphere into the World Ocean (Odum, 1986). These results confirm the importance of subarctic ecosystems for global biogeochemical carbon cycling.

One of the most important consequences of the global warming could be the shift of the subarctic front into the Bering Sea, which would lead to abrupt changes in habitats of pelagic and benthic communities, including many valuable fish species. Because the Bering Sea is an important fisheries region for several countries, where annually 3 x 10^6 t of fish is caught (Wilimovski, 1974), it is necessary to foresee the possible negative consequences of a warming climate in this region for the distribution and recruitment of the main commercially important species and for marine mammals and birds. The creation of forecasts for living marine resources under conditions of global warming would promote development of effective systems of adaptive options.

3.4 Palaeoecological studies and El Nino analogs

GCMs still lack the specificity to predict ocean currents and upwelling accurately. However, the palaeosedimentary record is available through analysis of sediment cores and can demonstrate how ecosystems changed in the past when the earth was warmer. This could improve understanding of the cause-and-effect relationships and possible feedback loops during times of rapid climate change.

Recent investigations of palaeo-productivity of the World Ocean, based on organic carbon accumulation rates (Sarnthein et al., 1987) have shown that the basic spatial distribution patterns of ocean productivity persisted through glacial and interglacial times. However, the ocean in glacial times was characterised by a more polarised productivity pattern than today, that is, by more productive upwelling cells and a slightly less productive ocean. This regime induced a bulk increase in the global carbon transfer to the deep ocean by about 2-4 GtC/yr and led, via an enhanced $CaCO_3$ dissolution and alkalinity in the deep ocean, to a significant extraction of CO_2 from the surface and intermediate waters and the atmosphere.

According to data from empirical palaeoproductivity curves from the east Atlantic (Sarnthein et al., 1988), this increase, to a large extent, was linked to enhanced carbon export from pulsating plankton blooms and resulted from a strong intensifying of oceanic upwelling in middle and low latitudes. It is confirmed by other palaeoecological analyses of zonal sea surface anomalies that show the average intensity of wind-driven coastal upwelling along the northeast Atlantic continental margin increased by at least 50% during the last Glacial Maximum (Lapenis et al., 1990; Sarnthein et al., 1987).

The interglacial reduction in bioproductivity of upwelling regions is one of the main factors leading to both the simultaneous rise in atmosphere CO_2 as recorded in ice cores and, with a delay of more than 1000 years, to a large-scale gradual CO_2 depletion of the deep ocean. This conclusion is based on the benthic carbon isotope record of CO_2. The decrease in new production matches a clear 13C depletion of organic matter, possibly recording an end of extreme nutrient utilisation in upwelling cells (Sarnthein et al., 1988). Based on these results and prognostic estimates of GCMs, Lapenis et al. (1990) predict a decrease in productivity of upwelling zones and, consequently, of the whole ocean under conditions of global warming.

In the Pacific Ocean the El Nino phenomenon is the dominant interannual climate signal. Thus, it has immense consequences in the Pacific and also in other parts of the world. Consequently it is important to know what will happen to this dominant short-term phenomenon under the postulated conditions of long-term global warming. El Nino is an oscillatory ocean-atmosphere interaction process, which exhibits maxima recurring at intervals of 2-10 years with extremes occurring at about 30 years. It is caused by disturbances in the global atmospheric circulation system. The spreading of warm waters from the north to the south along the coast of South America is accompanied by a rise of sea surface temperature of 5°-8°C, strengthening of water mass stratification and, consequently, by a sharp weakening of the intensity of coastal upwelling. These processes lead to mass development of the organisms of 'red tides' (dinoflagellates and symbiotic bacteria), changes in the series structure of the phytoplanktonic community, a sharp reduction of productivity in the coastal zone, mass mortality of fish and birds feeding on them, as well as to secondary contamination of the ecosystem with organic matter. Economic damage for the region is estimated at hundreds of millions of dollars.

Furthermore, evidence is mounting for teleconnections between El Nino and worldwide climate anomalies having the same characteristic periodicities (Glantz, 1984). These climate anomalies can be traced in all kinds of global palaeo-climate records, such as: varied sediments, coral records and tree ring cores.

Studies using ocean/atmosphere models, the low cadmium content in 400-year-old coral records (Shen et at., 1987) and tree ring analyses (Michaelson, 1989) indicate that the frequency and intensity of El Nino events since the little ice age (AD 1500-1850) were not too much different from those experienced in modern times. Hence, one can speculate that such frequency and intensity of El Nino phenomena will continue over the next 100 years regardless of the trend in global warming (Enfield, 1988).

3.5 Impacts on fisheries

Climate change is one of the most important factors affecting fisheries. The level of the impact varies widely and depends on attributes of the species as well as on their regional specificity.

Each population within a species is adapted to a hydrodynamic structure of specific temporal and spatial features. Changes in the ocean circulation may lead to the loss of certain populations, or the establishment of new ones, at the periphery of the species' area of distribution, in addition to changes in the location and absolute abundance of the population inside the boundaries of the species distribution areas (Troadec, 1989).

One useful approach to identify possible impacts is the method of historical analogs. It might be instructive to consider the biological consequences according to the decadal scale of warming that occurred during the first half of the present century. One of the most obvious consequences of that warming was the penetration of tropical and subtropical marine organisms into the temperate latitudes and the penetration of boreal organisms into the higher latitudes. This penetration was observed both in the North Pacific and North Atlantic; but warming impacts on the abundance of commercially important species can be either positive or negative, even for the same species, depending on region. For example, in the 1940s and 1950s, increased water temperature coincided with the largest year of biomass of Atlanto-Scandinavian herring, while at the same time the North Sea herring biomass fell to very low levels.

More recent fishery investigations in the North Atlantic have revealed clear climatic influences on growth, distribution and recruitment of commercially important fish stocks. For example, the 'seventies anomaly' (Rapp, 1984) brought about considerable impact on several fish stocks. This anomaly which started off East Greenland in the 1960s, propagated around Greenland and Labrador and into the North Atlantic Current, and reached the Barents Sea in 1979-80 (Dickson et al., 1984). In the late 1960s, this anomaly gave rise to extremely low temperatures in North Icelandic waters and was the probable reason for the change in summer distribution of the Atlanto-Scandinavian herring.

While these observations and others show consequences of fluctuations within a few years, it is likely that the impacts of a far more permanent change in temperature will be even more profound. A temperature rise of about 2°C may have substantial impact on the distribution, growth and reproduction of the fish stocks. The commercially very important fish stocks may take new spawning areas and their distribution patterns may change considerably.

In the Bering Sea, an increase was observed in pollock stocks in the 1970s and early 1980s. The high level of pollock stocks has been sustained despite the high levels of exploitation. This shows that the impact of climate may be manifested to a lesser degree in high productivity regions in the temperate and high latitudes such as the Bering Sea, than in less productive regions. Above all, in the most productive upwelling areas, the abundance of commercially important fish has remained at relatively stable levels (except for collapse of Peruvian anchovy in 1972-73).

Mariculture will also be affected by climatic change. Increasing near-shore temperatures resulting from the greenhouse effect could result in increased production of species in established higher latitude farming operations because of the prolonged availability of temperatures near to those optimum for growth. Cultivation of new species of temperate and subtropical origin could conceivably result as well. Finally a decrease in ice cover could substantially expand the geographic limits for potentially viable commercial operations for species such as salmonids, oysters and scallops (Frank et al., 1988). However, a significant increase in summer seawater temperatures in the Marlborough Sound in New Zealand, for example, may have serious implications for the salmon farming industry as these are already near the maximum for the successful cultivation of salmonids (New Zealand, 1989). For wild northern salmon, however, the strong homing instinct will prevent populations from southern areas which are warming up, from moving northward and they may finally disappear from different river systems as conditions become too severe for survival.

The impact of UV-B radiation is of concern because commercial and recreational species reside, during their very early life stages, in wetlands or in neuston, and/or feed on near-surface plankton during some life stage of their existence. Although most sea water may be relatively opaque to UV-B radiation, fish eggs and larvae that float close to the surface, as well as near-surface phytoplankton, zooplankton, corals and wetland plants, could be exposed to levels which will cause genetic abnormalities or direct mortality. Recent investigations have shown that UV-B radiation exposure could have a lethal effect on several marine species, including anchovy, shrimp, and crab larvae (Hunter et al., 1979). In connection with the expected increase in the intensity of UV-B radiation, there is a need for the full assessment of such effects on a population-wide basis for a number of vulnerable species.

3.6 Socioeconomic impacts

Changes in climate will alter the species composition and productivity of marine ecosystems supporting major fisheries. As a first approximation of the ability of societies to cope with changes in abundance and distribution of marine resources, one can look at the socioeconomic impacts of such changes in the recent past. Commonly cited examples of such changes include the collapse of the Peruvian anchoveta, the Californian sardine, the Alaskan King Crab, or the expansion of such fisheries as the Bering Sea pollock and the Chilean sardine. These provide important information about how societies have dealt with major changes (favourable as well as adverse) in fishery resources availability in the recent past. For example, as fish stocks have declined because of a combination of less favourable environmental conditions and overfishing, industries have often made the problem worse by continuing heavy fishing pressure, thus accelerating the collapse of the fishery. Frequently, industries as well as governments have been unwilling to accept the advice of scientists and take meaningful action to protect fish stocks. It is likely that global warming will produce collapses of some fisheries and expansions of others. The likelihood of collapse may be aggravated by inadequate management due to insufficient authority, unwillingness to act or lack of knowledge.

Fishery management is affected by shortcomings in the institutions for allocating scarce fish and by limited understanding of fish reproductive strategies with regard to environmental variability. If uncertainty with regard to the abundance of fish in the future is going to increase, regulatory institutions will have more difficulty in adapting. Many stocks will remain overexploited which is already the major cause of variability. On the other hand, improvement in the fishery management institutions will reduce variability as well as the adverse effects of equivalent changes due to global warming. There is progress on understanding fish and their environment. If the direction of potential changes in ocean circulation could be known, useful assumptions could be made on the likely changes in fish stock abundance and, hence, on fisheries management (Troadec, 1989). As an example of the interaction of fisheries, their environment and fishery management, the onset of a major El Niño event in 1972 coupled with overexploitation and apparent recruitment failure caused the Peruvian fishing industry to suffer a severe crisis in the following years (Caviedes, 1989; Barker and Chavez, 1986).

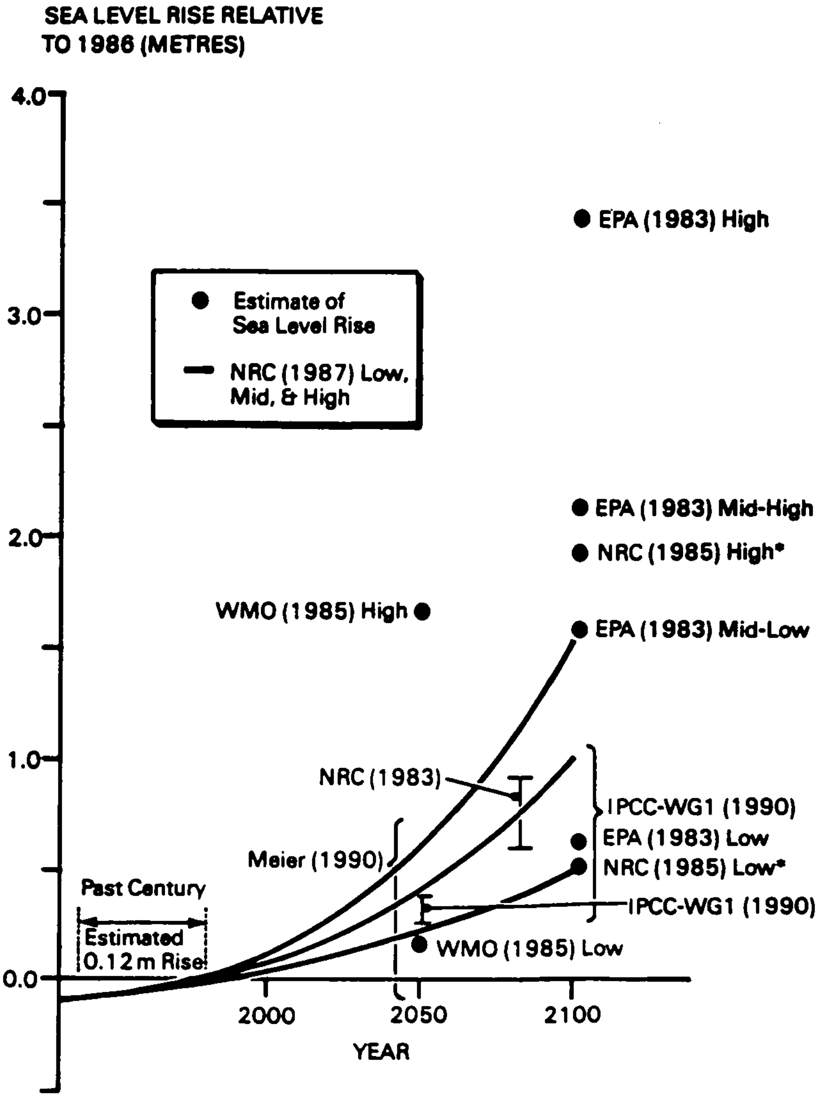
A major adverse impact occurs in societies having economies which are narrowly dependent on fishery resources and which are incapable of diversifying to other activities. This often is the case in developing countries bordered by major upwelling regions (eg Mauritania, Namibia, Peru, Somalia) (Troadec, 1989).

In general, societies have not coped well with changes in biological productivity, regardless of causes (natural or anthropogenic) (Glantz et al., 1987). Case studies of societal response provide insight into how people and their governments can better prepare for regional changes in distribution and abundance that might accompany global warming. If, in the face of climate change, it is desired to maintain fisheries at levels matching society's needs, higher levels of international collaboration might be needed, for which there, is no global analog from the past.

3.7 Impacts on navigation and territorial policies

At present, the northern ice-bound land borders of North America, Europe and Asia are highly sensitive national defence zones for all countries with Arctic territory. Security adjustments will be necessary if these coastal areas become navigable. National sovereignty issues regarding international fishing, hydroelectric power development, and freshwater transfers may be significantly altered. In the south polar region, warming may have implications for the future of the Antarctic Treaty which presently holds a number of territorial claims in abeyance. The possibility of climate-induced changes in access and prospects for resource development may result in altered national positions and competing claims. It is also recognised that the incidence of sea ice should decrease, providing benefits to navigation. Small sea-level rises may also **be** beneficial to port operations by enabling ships to **be** loaded to greater draught and still clear restricted channels. Transportation aspects are treated in Chapter **5.**

Figure 6.1 Estimates of future sea-level rise



Glacial Volume Estimate of NRC (1985) Augmented With Thermal Expansion Estimates of NRC (1983)

SOURCES:

Environmental Protection Agency, Projecting Future Sea Level Rise, 1983.

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Intergovernmental Panel on Climate Change — Working Group I, 1990 Meier, M.F. 1990 'Reduced Rise in Sea Level': *Nature*

Figure 6.2 Physical consequences of climate change

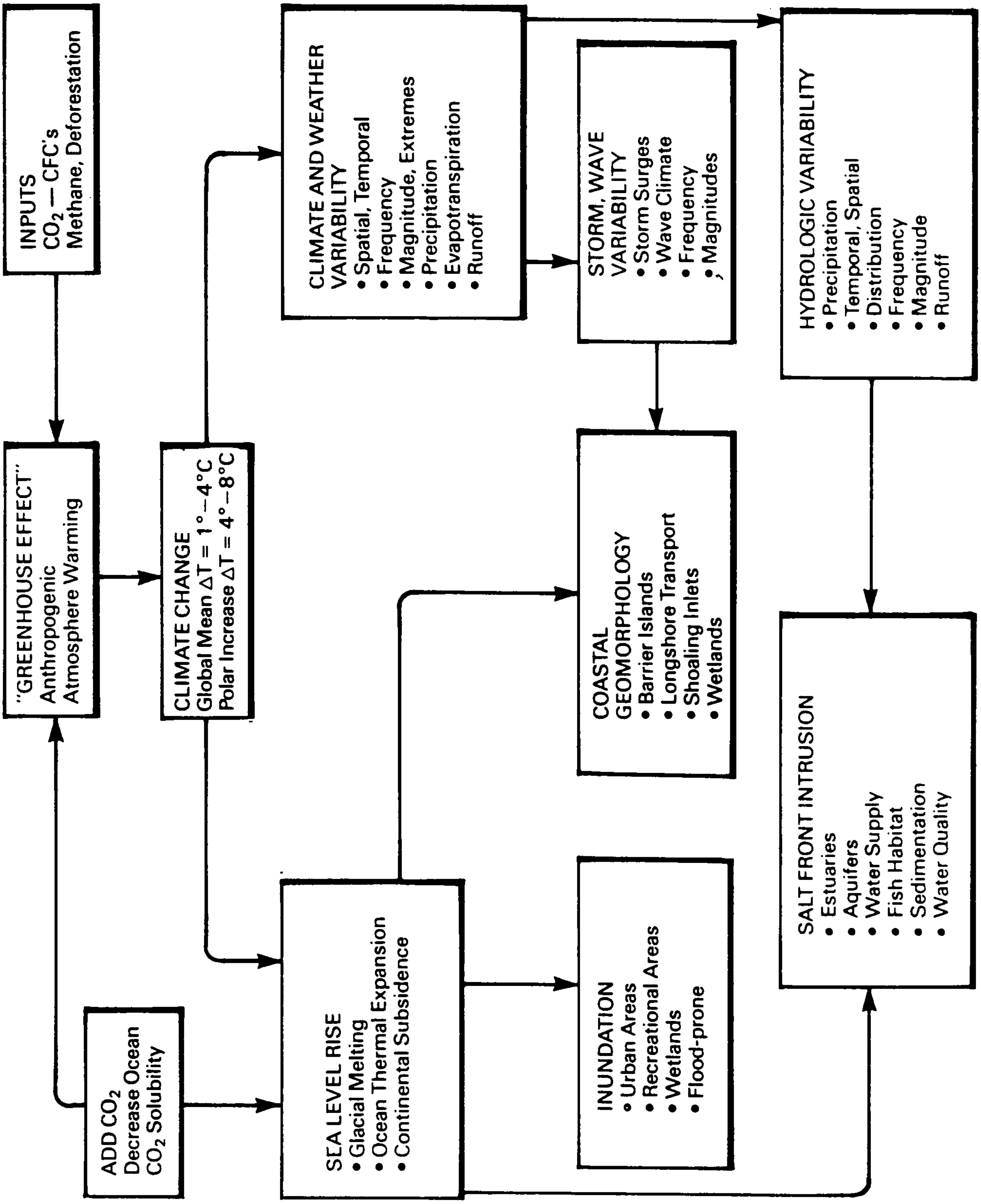
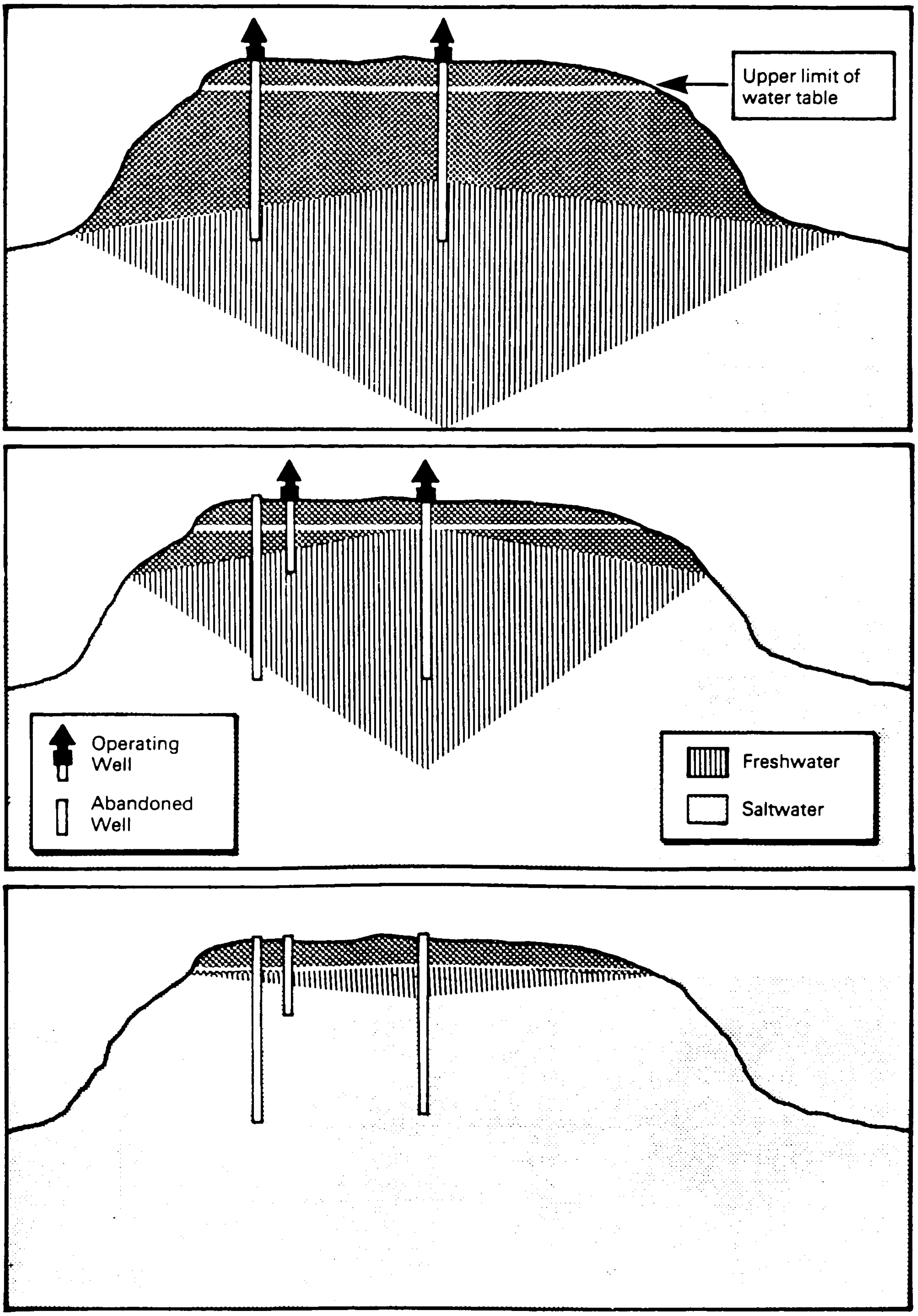
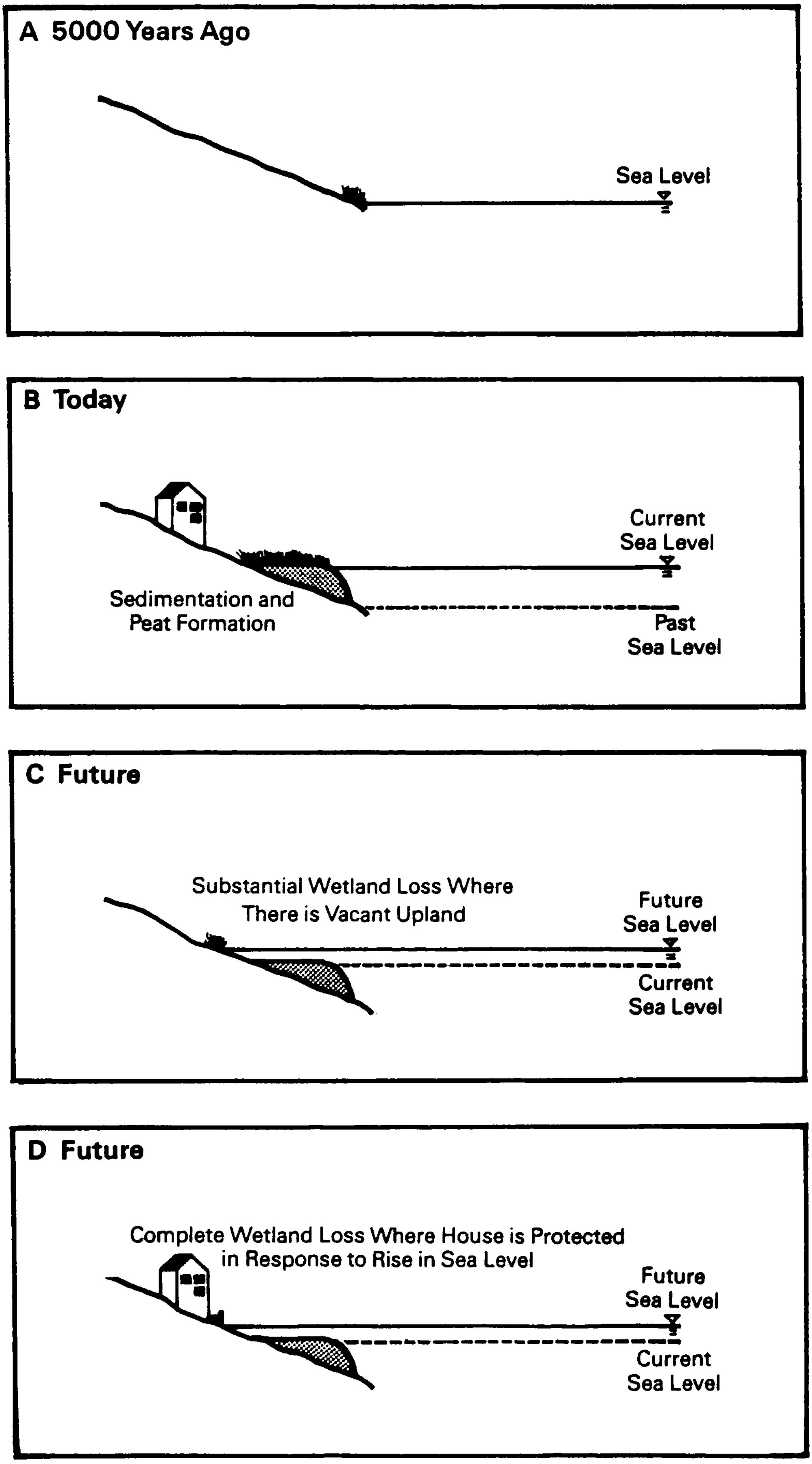


Figure 6.3 Impacts of sea-level rise on groundwater tables



Source: IPCC 1990 Miami Conference

Figure 6.4 Evolution of a marsh as sea-level rises



Source: Titus (1986)

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I

Chapter 7

Seasonal snow cover, ice and permafrost

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1 Introduction

This report examines the impact of climate change on the terrestrial component of the cryosphere including seasonal snow cover, mountain glaciers, ice sheets, frozen ground including permafrost (ground that remains frozen for more than one year) and seasonally frozen ground. Potential changes in these elements of the terrestrial cryosphere as a result of the projected changes in climate induced by enhanced atmospheric concentrations of greenhouse gases (GHG) are discussed. In addition, this report reviews the current understanding of the likely ecological and socioeconomic consequences of these changes.

The changes in climate that form the foundation of this chapter are primarily based on the scenario developed at the Villach 1987 meeting. Illustrative examples, however, will also make use of scenarios developed using palaeo-based reconstruction techniques and those produced by various computer simulations using general circulation models (GCM) depending on the specific scenario used by the referenced authors.

Currently, most of the land-based mass of ice is contained in the ice sheets of Antarctica and Greenland (Table 7.1). Compared to the total volume of the oceans, the ice volume stored in Greenland and Antarctica is relatively small at 2.1% (Oerlemans and van der Veen, 1984).

The largest areal extent of the snow is observed during the winter when seasonal snow cover occurs. The maximum extent of this snow cover can be as much as 62% of the Eurasian continent and virtually all of North America north of 35° during some portion of the winter season. The fact that seasonal snow in temperate latitudes is typically close to its melting point suggests that a temperature increase of even a few degrees could have a dramatic influence on its presence and its characteristics.

Seasonal snow cover, ice and permafrost will be significantly affected by the suggested GHG-induced climatic changes. The projected climate warming and changes in precipitation will, in general, decrease the global areal extent and masses of the seasonal snow cover, ice and permafrost. For most locations which currently experience a seasonal snow cover and seasonally frozen ground, the projected climate changes suggest a decreased duration of snow cover and increased length of the frost-frec season and, in some cases, a complete withdrawal of snow. In the case of glaciers and ice sheets the impacts of the projected changes in climate are complicated by the complex relationships between the dynamics of these ice masses and projected increases in temperatures and changes in precipitation characteristics. Although the relationships between permafrost and climate are complex, the projected climatic changes will most likely lead to increased degradation. The associated changes in seasonal snow cover, ice and permafrost have ramifications in terms of both local and global hydrology (eg meltwater flow, peak discharge, seasonal distribution of runoff and sea-level rise), nature and distribution of vegetation, as well as local and regional terrain stability (eg subsidence, landslides and other mass movements).

Changes in seasonal snow cover, ice and permafrost can also affect climate through various feedback mechanisms. Snow and ice surfaces have much higher albedos than do other natural land surfaces and, therefore, are capable of reflecting a greater percentage of the incident solar radiation. Decreasing coverage of snow and ice will, therefore, lead to an increase in the amount of solar radiation absorbed by the earth, thereby enhancing the global warming process. This may be further enhanced if increased cloudiness accompanies increased warming (see Working Group I Report). The additional long-wave radiation from the new snow-free land would be 'trapped' even more than at present if cloudiness also increases. Furthermore, degradation of permafrost could alter atmosphere-biosphere fluxes of GHG (eg methane), thereby influencing the amount and rate of global warming. Increased rates of melting, however, will reduce the potential climatic warming as energy is used to melt the ice.

Another factor that should not be neglected in this assessment is the influence of human activities on seasonal snow cover, ice and permafrost. The influence is felt mainly locally through anthropogenic changes in the surface and quantity and quality of the snow or ice. These changes disrupt the surface (change in albedo, exposure of ice mass etc) and thereby alter the ablation and degradation processes. Examples of these disturbances are abundant, ranging from the impact of building snow roads and ice bridges, and of traffic on glaciers and ice sheets, to surface disruptions during the building of structures and pipelines. In the case of snow, human activities such as building of structures and certain

Table 7.1 Relative extent of terrestrial areas of seasonal snow cover, ice and permafrost (after Washburn, 1980a and Rott, 1983).

	Area (million km^2)	Volume (million km^3)
Land ice		
Antarctica	13.9	30.1
Greenland	1.8	2.7
Small ice caps	0.35	0.2
Mountain glaciers	0.2	0.03
Major permafrost region		**Percentage underlain by permafrost**
USSR	16.84	50
Canada	9.38	50
China	9.38	22
Greenland	2.18	100
USA (Alaska)	1.52	82
World land area	140.7	20-25
Northern hemisphere	7.6*	
Continuous	17.3*	
Discontinuous	2.33*	
Alpine permafrost		
Land ice and seasonal snow	**Area**	**Volume**
Northern hemisphere		
Early February	46.3	0.002
Late August	8.7	
Southern hemipshere		
Late July	0.85	
Early May	0.07	

* Approximate

types of logging practices can actually increase the amount and duration of snow cover and, thereby, also influence any underlying permafrost.

The relationships between the dynamics of climate and seasonal snow cover, ice and permafrost are exceedingly complex and, because of their nature (eg remote, massive, dynamic etc), difficult to study. Observation techniques and analysis methodologies that will provide a better understanding of the dynamics of these relationships are relatively new or under development and therefore have not been widely used.

Limited research and basic data combined with the lack of involvement of representatives from social and economic communities in programs which examine the implications of the suggested changes lead to conclusions which are in most cases highly speculative. This does not diminish in any way the need for effective and timely responses. With climatic changes, seasonal snow cover, ice and permafrost will be affected and the suggested changes are qualitatively plausible. Actions to solve problems cannot be made until the causes of the problems are more than speculative. This alone suggests that decisive actions are required to obtain more comprehensive information and to undertake directed, integrated research. Long-term research should be designed to better define the dynamics of seasonal snow cover, ice and permafrost and the bounds of possible response strategies.

2 Environmental impacts

2.1 Seasonal snow cover

Seasonal snow cover is for the most part a transient element of the earth's surface persisting at one location anywhere from a few days to a major portion of the year. The areal extent of seasonal snow cover is also highly variable (Fohn, 1989) changing continually during a particular season and from one year to the next. These temporal and spatial fluctuations are in response to the variable microclimates and terrains typical of those areas which experience seasonal snow cover.

The impacts that GHG-induced climatic changes would have on seasonal snow cover, particularly at higher latitudes, are not known with certainty. In those areas where spring temperatures are expected to increase with early spring snowfalls becoming rain events and, where warm air advection events could become more frequent, the duration of snow cover will decrease. In those areas where temperatures are projected to remain below or at freezing and where winters are expected to be warmer but wetter, the snow pack will increase and hence take longer to melt in the spring. Increased snowfall and suggested changes in the snow cover dissipation could have serious repercussions by delaying planting and access to pastures and rangelands.

Computer-generated climate scenarios provide some indications of possible impacts of GHG-induced climate changes on seasonal snow cover at a continental scale (Schlesinger, 1986). When interpreting these results it should be noted that current versions of these models have rudimentary simulations of the exchanges between the ocean and the atmosphere including the impact of sea ice and, because of their spatial resolution, limited representation of potential regional impacts and elevation differences. As would be expected under the influence of global warming, the simulations indicate that the area covered by snow will decrease in both the southern and northern hemispheres. In terms of the mass of snow, however, the responses are less uniform. In general, within the Northern Hemisphere, a decrease in the mass of snow is indicated, whereas an increase occurs within the Southern Hemisphere. These changes in mass, however, are not uniform but, to some degree, depend on latitude, elevation and season. Throughout the year, snow mass north of 30°N latitude and north of 68°S latitude is expected to decrease in response to climatic changes, while snow mass is expected to increase over Antarctica, south of 68°S latitude.

As depicted by computer simulation (note limited modelling of orographic features in GCM), changes in snow mass during the winter within the Northern Hemisphere do not appear to be related to elevation; however, during the summer, elevations below 1500 m predominantly have snow mass decreases, while locations at higher elevations show both increases and decreases. The increases in Northern Hemisphere snow mass occur over the Greenland interior in both summer and winter. In the Southern Hemisphere, snow mass increases are suggested during summer and winter in the interior of Antarctica above the 400 m level with decreases around the Antarctic coastline.

The suggestion that snowfall along the coastline of Antarctica will decrease as a result of projected climatic changes is debatable. Projected reductions in the sea ice cover around the Antarctic continent as a result of climatic changes will increase the area of open water, thereby providing an additional moisture source for increasing atmospheric moisture and, thus snowfall on the adjacent land or ice sheet.

Possible impacts of GHG-induced climatic changes on seasonal snow storage and the snowline have been estimated for New Zealand (Fitzharris, 1989) using a snow wedge simulation model with temperature increased by 3°C and precipitation by 15% above current levels. When applied to the South Island, this model suggests that the snowline will rise 300-400 m, with a decrease in snow accumulation below 2300 m. Seasonal snow storage, which now averages 350 mm, will decrease to 190 mm, and the area covered by winter snow will be halved.

Within the Alps, Kuhn (1988) suggests that a permanent snow cover will be observed only at altitudes above 1500 m by the year 2050 as a result of the projected changes in climate. An analysis of the recent seasonal distribution of snow cover at 20 stations in the Alps (Fohn, 1989) found large seasonal fluctuations with no long-term trend. The last five to seven winters did, however, clearly show lower than normal snow depths on 1 January. Despite the fact that these depths were not outside the range of normal fluctuations, continuation and intensification of this trend would have serious ramifications to snow dependent components of the Alps economic communities (eg skiing and tourist industries).

Owing to its high air content, dry snow is a very effective insulator for the ground. Significant decreases in snow cover will result in increased susceptibility of agricultural crops (eg winter wheat), natural ecosystems perennial species (eg trees and shrubs) and animals (eg hibernating species) to adverse effects of cold temperatures and frost where freezing temperatures continue to occur. Lack of sufficient insulation by snow cover has been cited as a factor contributing to reductions in forest health and losses in overwintering agricultural crops. Lack of insulation from snow cover has also led to damages to urban infrastructure and to other facilities as a result of frost heave.

Climate models have shown that snow cover, through its influence on surface albedo, is a critical factor in the local and global climate system

(Budyko 1969; Manabe and Wetherald, 1980), particularly at high latitudes/altitudes where the ground may be covered with snow from 6-9 months each year. This albedo-temperature feedback mechanism is related to the fact that snow, depending on its quality, has a very high albedo (0.3-0.9) reflecting the sun's radiation 2-3 times more than grassland and soil. In addition, although snow absorbs and emits long-wave radiation most effectively, the emission is limited by the fact that the snow surface temperature is below 0°C. Based on this limitation, snow cover hampers a fast warming of the adjacent air relative to that which would occur from a warmer, snow-free surface.

Changes in the duration and area covered by snow could, therefore, have significant impact on local, regional and global climates (Fohn, 1989). Where climatic warming leads to decreased snow cover a lowering of the surface albedo will occur. This in turn would result in more absorption of solar energy, and thus increased warming of the adjacent air (positive feedback). In those areas where climatic warming results in increased snow cover, surface albedo would increase which would decrease the solar radiation absorbed by the surface. This would reduce warming of the adjacent air.

Any increase in precipitation should lead to more frequent summer storms and more freezing rain in the autumn. Although the duration of the snow cover season may be shorter, substantial precipitation increases could lead to more snow accumulation. Global warming might advance the melt season so that melt will no longer occur within the intense solar insolation period near the solstice. Snow accumulations, which formerly provided late-season local water sources required to maintain wetlands, may not persist (Woo, 1989).

2.2 Ice sheets and glaciers

The relationships between climatic changes and ice sheet and glacier responses are complex and, because of relatively limited monitoring and research, are not yet fully understood. Projected increases in air temperature, because of its relationship with the surface energy budget, may increase melting rates. However, other factors such as changes in winter precipitation and surface albedo and in the case of ice sheets, iceberg discharge and ocean-ice shelf melting and freezing, add to the complexity of the response.

The bulk of the earth's ice mass is stored within the Antarctic ice sheet (see Table 7.1). The continent, which is approximately 98% ice covered, is naturally divided into two parts: an eastern portion rests on continental crust which, without an ice load would be dominantly above sea-level; and a large western portion which is underlaid both by continental crust and ocean. A review of available evidence from mass balance studies (Budd and Smith, 1985) suggests that the rate of accumulation of ice and the total rate of discharge are nearly in balance for this ice sheet with a discrepancy from 0-20% (due mainly to uncertainties in iceberg discharge, accumulation data, and in the rates of melting below the major ice shelves). The Antarctic ice sheet, however, is probably still adjusting its mass balance to changes that were initiated hundreds or even a few thousand years ago (it is quite probable, dynamically, that it is in fact still responding to the transition out of the last glacial period, over 11,000 years ago).

The Greenland ice sheet is smaller with portions of the continent in the coastal areas permanently ice free. It is not possible at present to estimate reliably the mass balance of the Greenland ice sheet because of a lack of comprehensive observations. Recent estimates (Zwally et al., 1989) using satellite observations, however, indicate that the Greenland ice sheet has thickened by approximately a quarter of a metre a year since the late 1970s. Zwally et al. hypothesise that the observed thickening is a direct measure of the amount of new snow accumulating on the ice sheet.

Characteristics of the Antarctic and Greenland ice sheets are summarised in Table 7.2. Apart from the major ice sheets, small ice caps are found on some Canadian, Norwegian and Soviet islands (eg Ellesmere Island where three ice caps cover an area of more than 20,000 km^2 and Svalbard, where three ice caps cover 15,000 Km^2 of a total 36,000 Km^2).

The effects of GHG-induced climatic changes on ice sheets will be to bring them out of balance (mass balance) and to gradually warm them up (Oerlemans and van der Veen, 1984). Surface melting with runoff to the sea, particularly for Antarctica, is unlikely to be significant during the next century. In the case of the southern portion of the Greenland ice sheet, which has huge ablation zones in the true temperate glacier sense, surface melting with runoff may be significant (possible contribution to sea-level rise in the next hundred years).

The relation between precipitation changes and temperature changes in polar regions is of central importance to understanding current and future behaviour of the ice sheets (Zwally, 1989). In polar regions, enhanced precipitation is associated with warmer temperatures because of the greater moisture capacity of warmer air and the increased

Table 7.2 Characteristics of the Greenland and Antarctic ice sheets (based on Oerlemans and van der Veen, 1984).

	Greenland	Antarctica
Area (million km^2)	1.8	13.9
Mean ice thickness (metres)	1530	2160
Ice volume (million km^3)	2.7	30.1
Maximum surface elevation (metres)	3300	4000
Annual accumulation (cm ice depth/year)	34	17
Loss of ice (%)		
Calving	50	99
Melting	50	1

availability of moisture as the ocean area covered by ice declines. Schlesinger and Mitchell (1987) suggest that the increase in precipitation is 5% to 20% per degree Kelvin. Owing to the projected changes in temperature, precipitation and cloudiness and the influence these have on ice sheet accumulation and ablation, the dominant short-term effect of these changes may be growth of both the Greenland and Antarctic ice sheets, but in the case of Greenland may be offset by increases in melting in marginal areas.

The warming of the ocean as a result of climatic changes may have an important impact, particularly on the west Antarctic ice sheet. For a significant impact, however, the increased temperatures must reach the deeper layers of the ice sheet, a process which could take several thousand years.

Using a scenario based on palaeo-based reconstructions, Kotlyakov and Grosswald (1981) suggest that in Greenland the altitude at which the ice sheet will continue to accumulate ice will rise 250-650 m under the impact of projected climatic changes. This level of change could lead to a two-fold growth of the ablation area and an annual lowering of the Greenland ice sheet at an average rate of 0.5-0.7 m/year. Other calculations for the Greenland ice sheet (Ambach, 1980) indicate that as a result of a 3°C increase in surface air temperature and a 12% increase in precipitation, a substantial decrease in its mass balance may result in a decrease of 3% in ice volume over the next 250 years (which could contribute to a rise in sea-level of approximately 0.2 m).

Braithwaite and Olesen (1984) have shown that temperature and ablation of Greenland ice are related. They hypothesise that a 3°C temperature increase from 2°C to 5°C would result in a 100% increase in the melt rate (from 20 kg/m^2/day to 40 kg/m^2/day). The role of sensible heat flux is considered to be of paramount importance in determining the state of balance of the Greenland ice sheet (as well as other ice sheets), however, this effect is still not well understood.

Projected changes for the Antarctic ice sheet are complex. A preliminary assessment that assumes an increase in surface air temperature of 3°C and a 12% increase in precipitation during the next 100 years suggests an increase of the Antarctic ice volume of approximately 0.5% after 250 years (which could contribute to a decrease in sea-level of approximately 0.3 m). Kotlyakov and Grosswald (1981) hypothesise that the eastern Antarctic ice sheet may remain unchanged as a result of the projected climatic changes.

In contrast the western Antarctic ice sheet like other marine ice sheets, is inherently unstable and could be affected by ground-line retreat and by the rapid dispersal of ice into the surrounding oceans by way of relatively fast-flowing ice streams (Bindschadler, 1990). Rapid changes recently observed on the west Antarctic ice sheet indicate possible instability. These observations, combined with the potential socioeconomic consequences should such a collapse occur (an immediate surge in global sea-level of up to 6 m), however, suggest that the west Antarctic ice sheet should continue to be closely studied.

Climate does influence the dynamics of glaciers and small ice caps through its impact on the amount of snow that collects on their surfaces and the amount of snow and ice lost by melting (Paterson, 1981; Oerlemans and van der Veen, 1984). The response of a particular glacier or ice cap to climate, however, is complicated owing to the large number of other factors (eg glacier geometry, debris cover, ice thickness-mass balance feedback, and calving).

The annual mass balance of a glacier is defined as the difference in water equivalent between accumulation and ablation at the surface, summed over the area of the glacier. Accumulation normally is a result of snow which is transformed into ice; however, avalanches, rime formation and freezing of rain within the snowpack also add mass. Melting followed by runoff, evaporation, removal of snow by wind, sublimation and calving of icebergs are primary ablation processes. All of these accumulation and ablation processes will be affected by climatic changes with resulting impacts on glacial and ice cap masses.

Glacier mass balance, although complicated by background 'noise' inherent in glacier dynamics due to local effects, is considered sensitive to climate (temperature, precipitation, cloudiness etc) and thus is an effective indicator of climatic change. The Permanent Service for the Fluctuation of Glaciers (now the World Glacier Monitoring Service) has been archiving mass balance data for approximately 100 glaciers. Examination of the trends of mass balance data for five glaciers with relatively long records (since 1946) indicates decreasing values over the last few decades. Shrinkage has been most pronounced at mid-temperate latitudes (eg 0.37 m/year from 1934 to 1982 at Hintereisferner in the Austrian Alps) and relatively minor at higher latitudes (eg 0.06 m/year in the Canadian Arctic and 0.25 m/yr in Scandinavia (Norway)).

Projected increases in precipitation may cause some glaciers to advance despite increased ablation. This may presently be reflected by the increase in mass balance of certain Canadian and US glaciers, particularly those dominated by the effects of winter snowfall (eg Blue Glacier in northwest US and Sentinel Glacier in southwest Canada).

Most Andean glaciers have receded dramatically from their positions in the mid-late 19th century (Clapperton and Sugden, 1988) with the period of most rapid recession being between the early 1930s and the early 1960s. Colombian glaciers have decreased in extent by one-third between 1939 and 1969 (Wood, 1970). The complete disappearance of many small glaciers and perennial snowfields in the Pico Bolivar area of Venezuela has resulted as the snowline has risen approximately 6 m per year in this area during the period 1885-1972 (Shubert, 1972). In New Zealand some glaciers are advancing whereas Heard Island (subantarctic island) glaciers are retreating.

A preliminary assessment based on a climatic change scenario which includes a 1°C increase in temperature and an increase in accumulation of 150 mm/year, suggests that an increase of 190 m could occur for the height above which glaciers may realise a net gain in mass in the European Alps (National Research Council, 1985). The projected increase in height is 230 m when the added accumulation was modelled as occurring in the winter months exclusively.

Following the palaeo-based reconstructions of Budyko et al. (1978), Kotlyakov and Grosswald (1981) conclude that the response of glaciers will depend on their type and geographic location. The net mass balance of mountain glaciers in the Eurasia temperate zone will remain essentially unchanged by the 2020s since increases in ablation will be balanced by suggested increases in snowfall. The ablation on the ice caps in the Soviet Arctic archipelagoes is expected to reach 4-6 m (water equivalent) of which only 10-15% will be balanced by increased accumulation. This would suggest that the archipelagoes, with their mean present-day ice thickness of 150-250 m may become completely free of glaciers within the next several decades.

Kuhn (1989) examined the impact of a particular climate scenario for the year 2050 (including a temperature increase of 3°C) on alpine glaciers in Austria. Based on this analysis, he hypothesised that little or no ice may be found below 2500 m and only slightly more than half of the existing glacier surfaces will remain ice covered. The areas from which glaciers retreat would be converted into morphologically highly unstable moraine slopes and forefields which could contribute to landslides, mudflows and increased sediment loads in rivers. At high elevations and high latitudes summer conditions are such that the surface energy balance does not support releases of significant quantities of meltwater. At lower elevations and latitudes glacier ice is exposed to temperatures sufficient to allow melting for several months of the year and, therefore, significantly impacts local and regional hydrology.

The rate of production of meltwater from glaciers and small ice caps is influenced by the incoming solar radiation and by the albedo of their surfaces. Observed data indicate that warmer than average summers will tend to cause significant increases in runoff. The effects of changes in precipitation on these ice masses, however, are less straightforward. Changes in precipitation will influence ablation and meltwater production from glaciers and ice caps by affecting surface albedo and indirectly by associated changes in cloudiness and their effects on incoming solar radiation. For example, the previously mentioned increase in snow cover and/or longer persistence of the snow cover in the spring could reduce early season melting and meltwater release from these ice masses.

One concern regarding the melting of ice sheets and glaciers is related to the impact of this additional water on sea-level. Little if any sea-level change currently observed is caused by wasting of the Greenland ice sheet (a stable or slightly positive state of mass balance), and the Antarctic ice sheet, as mentioned above, is most likely growing, taking water out of the sea. The glaciers and small ice caps of the world outside of Greenland and

Antarctica, however, have in general been shrinking during the past 100 years (Meier, 1984). Sea-level is currently thought to be rising at a rate of 1 to 3 mm/year (Meier, 1990) although this change is far from uniform throughout the world. The rise in sea-level currently observed could be partly attributed to the wastage of alpine glaciers located in the mountains ranges along the Gulf of Alaska, in Central Asia, and from the Patagonian ice caps. Also contributing to the rise in sea-level are such processes as thermal expansion of sea water or the tectonic effects, isostatic rebound, erosion, and sedimentation. Estimates of the effect of current ice wastage compared with that projected under conditions of doubled CO_2 concentrations are shown in Table 7.3.

Evidence of extensive forest cover (dated at 3000 year bp) beneath present-day glaciers in the Rockies and coastal mountains in western North America provides further evidence that within the recent past, vast mid-latitude areas were deglaciated. If such déglaciation occurred today water supplies and local climates could be dramatically changed in these regions.

Changes in the amount of melt occurring and the characteristics of glacier or ice sheet surfaces can affect the local and possibly the global climate (Oerlemans and van der Veen, 1984). Glaciers and ice sheets influence climate through their impacts on the local and global energy balance. Energy is required to melt ice and this energy (radiation, sensible and latent heat) is taken from the surrounding air (directly or indirectly) and water. Increases in the amount of ice experiencing melt could therefore lead to a general cooling of the atmosphere and surrounding waters. This potential cooling will have a greater effect on local climate than global climate as melting 1% of the terrestrial ice in 100 years requires a global average of 0.06 W m^2 which is negligible compared to the CCyinduced heat fluxes.

Another factor to consider regarding the impact of changes in these ice masses on the energy balance is that snow and ice that make up the surfaces of glaciers and ice caps reflect more solar radiation than other natural surfaces (see previous discussion on seasonal snow cover). Decreases in the quantity and quality of the surfaces of these ice masses could enhance the warming effect.

2.3 Permafrost

2.3.1 Nature, extent and stability of permafrost

Permafrost is the term used to describe ground (soil or rock) that remains at or below 0°C throughout the year for at least two consecutive years. Permafrost usually contains ice in various forms, from ice held within soil pores to massive bodies of more or less pure ice many metres thick. The presence of ice in permafrost makes it behave uniquely as an earth material, and also makes it sensitive to climatic warming. Dramatic visual evidence of permafrost terrain such as pingos, patterned ground, earth hummocks, ice wedges, palsas, mass movement and thermokarst features are all dependent to some extent on the presence of ice (and especially phase changes of the ice) in the ground.

Evidence of the existence of permafrost has been dated as far back as 600 million bp (Tarling, 1980). It does appear, however, that permafrost has not persisted throughout geological time, but occurred rather sporadically without a discernible pattern. Most of present permafrost is many thousands of years old and formed during the last glacial period or Pleistocene. Permafrost containing large amounts of ice and vulnerable to thaw is often of more practical significance. Today, permafrost underlies 20-25% of the land surface of the earth (Figure 7.1) in the polar and circumpolar regions, and in alpine areas at lower latitudes. Freezing conditions in the surface layers of the earth (seasonal and perennial) are also found at temperate latitudes, and at high altitude in the tropics. Elsewhere permafrost is found in Antarctica, on high-latitude islands, in the mountain ranges of Scandinavia, Europe, North America, Central Asia, Chile, and South Africa, and scattered low-latitude peaks (eg Fujiyama and Kilimanjaro). In ice-covered regions permafrost occurs at glacier margins and in nonglaciated oases.

Permafrost is also widespread beneath the seabed in the Arctic Ocean (Sellman and Hopkins, 1984). However, because of freezing point depression as a result of the salts present, the occurrence of extensive ice-bonded material is limited to the continental shelf areas which were exposed to sub-areal conditions during the Pleistocene (Hunter, 1988). Such permafrost (submarine permafrost) may be considered as relict (permafrost which formed under past climatic conditions and which could not form under present conditions) and is undergoing degradation (ie thawing). In coastal areas where the sea normally freezes down to the seabed, permafrost is contemporary.

Table 7.3 Effect of terrestrial ice sheets on sea level, adapted from a workshop (National Research Council, 1985) and Meier, 1990.

Ice mass	Present yearly effect on sea-level (mm/year)		Cummulative effect by Year 2100 for 2 x CO_2 atmosphere (metres)	
	NRC	Meier	NRC	Meier
Glaciers and small ice caps	0.2 to 0.8		0.1 to 0.3 (0.3 to 0.6 for complete melt)	0.02 to 0.3
Greenland ice sheet	-0.5 to +0.3	-0.2 to -0.7	0.1 to 0.3	-0.04 to 0.2
Antarctica	-1.2 to 0.0	-0.5 to -1.0	-0.1 to 1.0 (0.0 to 0.3 most probable)	-0.5 to -0.1
Total	-1.5 to +1.1		0.1 to 1.6 (0.2 to 0.9 most probable)	-0.5 to +0.4

The greatest permafrost thicknesses occur as a result of a combination of low surface temperature, low geothermal heat flow and relatively high thermal conductivity and are also related to the non-glaciated past; permafrost extends to a depth of 1000 m or more in Canada (Judge, 1973), to 1500 m in the USSR (Melnikov, 1978), and 100-200 m in China (Youwu and Zhou, 1983). The development of permafrost to such thicknesses requires the persistence of suitable climatic conditions on a geologic time scale, thus, to some extent, the depth of permafrost is dependent on its age (Kudriavtsev, 1965; Melnikov, 1978; Judge, 1973).

Although permafrost is directly temperature-dependent, its occurrence also depends on a number of local and other climatological factors (Washburn, 1979; Williams and Smith, 1989). The relationships between the different factors and permafrost are schematically represented in Figure 7.2 (Nieuwenhuijzen and Koster, 1989). Some of the factors are relatively static in time (eg topography, altitude and latitude), although the majority are time-dependent and closely interrelated. Another complicating factor is the relict character of a large part of permafrost which has no clear relationship to present day climatic parameters. This greatly complicates the assessment of the effects of climatic changes on permafrost as changes in different variables may either enhance or counteract each other.

Maps showing the distribution of permafrost are based on broad correlations with climatic data. For example, the 'southern limit' of permafrost is often represented by the -1°C mean annual air isotherm (Brown, 1978; Gavrilova, 1981), although occurrences of permafrost are known south of this (eg Zoltai, 1971). Investigators concerned with mapping permafrost at small geographical scales generally use a classification scheme in which permafrost is characterised as continuous, discontinuous or sporadic. Maps employing such classifications usually depict specific zones at different latitudes, although in reality there is a gradual transition from the seasonally frozen ground of temperate regions to the perennially frozen ground of the polar regions. The zones are meant to convey the relative areal dominance of permafrost and permafrost-free conditions.

Wherever the average annual temperature is within a few degrees of 0°C, local variations in surface conditions (vegetation, topography, hydrologic conditions, solar exposure and snow cover) determine where the ground thermal regime can sustain permafrost. Where conditions are not homogeneous, permafrost can occur in patches. At higher latitudes, where temperatures are lower, bodies of permafrost become more frequent and larger in extent. Even in very cold regions, however, there are still gaps in the permafrost, due primarily to the presence of water bodies (streams, rivers and lakes) which do not freeze to their bottom in winter. These non-homogeneous characteristics of permafrost coupled with the scattered nature of direct observations, make precise mapping of permafrost and ground thermal conditions difficult. They also make it difficult to develop an accurate geographic prognosis for permafrost responses to climatic changes.

Although there is broad and intuitive agreement about the concept of permafrost zonation, satisfactory operational definitions have not often been presented in the literature. This has lead to non-standardised mapping criteria.

Snow cover, through its influence on ground temperatures, can significantly affect permafrost occurrence. In discontinuous and sporadic permafrost areas, snow cover may be the critical local factor determining whether permafrost is present or not. In the colder regions of more continuous permafrost, it influences the depth of the active layer. A sufficient blanket of snow provides insulation to the ground, thereby keeping it warmer than that which would occur under less abundant snow cover or snow-free conditions. Goodrich (1982) concluded that mean annual ground temperatures are most strongly influenced by the timing of snow accumulation in autumn and early winter, and by the maximum depth attained over the winter. In his calculations, a doubling of the snow cover from 25 to 50 cm increased the mean annual surface temperature by several degrees. Rapid build-up of snow in autumn augmented this effect.

In some cases an abundance of snow may promote the occurrence of permafrost. Under these conditions the snow pack could persist until later in the spring or early summer. This delay would reduce the amount of warming of the ground that can occur (Gold, 1967; Goodwin and Outcalt, 1975).

Rainfall can also influence the permafrost by increasing ground temperatures. An increase in precipitation during the period when permafrost is not covered by snow tends to reduce ground surface temperatures due to associated cloud cover which reduces the incident solar radiation. Rain falling on snow also promotes the lowering of ground temperatures by reducing the insulating quality of the snow.

Vegetation and the organic layer play a role in the ground thermal regime in two ways: as part of a 'canopy above the surface, or as a surface layer over the mineral soil. A vegetation canopy reduces the amount of solar radiation reaching the ground surface, and will have a variable effect on the accumulation and persistence of snow cover (eg Luthin and Guymon, 1974; Gavrilova, 1978; Rouse, 1982). Interception of precipitation and transpiration by the canopy also influence the ground thermal regime through evaporation and the water balance. Rouse (1984) found that summer soil temperatures beneath an open spruce forest were lower than adjacent tundra as a result of radiation interception by the canopy, higher evaporation from the wetter surface and the greater roughness of the forest which increases turbulent heat loss to the atmosphere. Brown (1965) concluded that variations in the vegetation canopy were a relatively minor influence on the ground thermal regime compared to the surface organic layer.

The presence of sporadic or discontinuous permafrost is commonly associated with an organic surface layer, usually peat (Brown, 1973, 1978; Fitzgibbon, 1981). The particular influence of organic soils (especially peat) on permafrost is attributed to: (i) the low conductivity of organic soils relative to mineral soils; (ii) the effect of seasonal variations in the water content of organic soil on its thermal conductivity; and (iii) the seasonal evaporative regime of the surface as controlled by climatic and surface factors (Riseborough and Burns, 1988).

Seasonal variations in moisture content of the organic layer (thermal conductivity of peat 5-25 times that of wet or dry frozen peat) give it a low thermal conductivity in summer, inhibiting warming of the ground. In winter the wetter organic layer freezes, increasing its thermal conductivity thereby enhancing cooling of the ground. The mean annual ground temperatures under peat are, therefore, lower than under adjacent areas without peat, and permafrost can persist at sites with positive mean annual surface temperatures (up to approximately +2°C). Furthermore, the generally low thermal conductivity of surface organic materials helps to preserve relict permafrost beneath it.

In some areas at least, the direct effect of vegetation may be less important than its role in snow accumulation (Smith, 1975; Rouse, 1984). Where the canopy can trap a deep blanket of snow, the soil will be considerably warmer in the winter than in the nearby tundra (Rouse, 1984). Interception of snow by trees in areas of extensive boreal forest can reduce the snow cover (French 1976), lowering ground temperatures. Alternatively, a deeper snow cover may have a net cooling effect if spring snowmelt is prolonged, holding the ground surface temperature at or below 0°C when air temperature is high in early summer. The interplay of these factors contributes to the uncertainty over the precise implications of climatic changes for permafrost.

Permafrost does influence vegetative cover, although playing a relatively minor role compared to climate and soil type. The shallow active layer is a nutrient source for vegetation, maintaining water and nutrient supplies close to the surface. The permafrost layer is relatively impermeable and acts as a barrier to the movement of water and nutrients and restricts root growth to the active layer. Low active layer temperatures reduce nutrient availability and the rate of decomposition. Ecosystems such as black spruce and forest floor moss have adapted to the presence of permafrost and often sustain permafrost as well as being sustained by it.

Forest distribution near the tree line is commonly related to permafrost regimes (McKay and Baker, 1986). The abundant growth of mosses and the accumulation of undecomposed organic material at the surface in arctic regions provides insulation against summer thaw and increases soil moisture (Kryuchkov, 1978). In a study of forests and vegetation in the Mackenzie Valley, Zoltai and Pettapiece (1973) noted that taller trees were associated with deeper active layers, but die-off occurred when moss layers developed. Some species such as trembling aspen are restricted to areas where the permafrost table is well below the level of rooting. Other species such as spruce can grow on much thinner active layers.

Finally, permafrost as a climatic phenomenon is an indicator of both present and past climates. The upper layer (10-20 m), subject to annual temperature fluctuations, reflects current climatic conditions of an area - both regional (macroclimate) and site-specific (microclimate). At greater depths the temperature regime reflects the climatic conditions of earlier periods. Relict permafrost, usually found at significant depth, currently exists in regions which should be free of permafrost according to the present energy budget; therefore, it is normally unstable and slowly degrading.

Temperature records from oilwells and other boreholes in Alaska, Canada, Norway and Russia clearly show that the upper layers of permafrost (20-100 m) have increased in temperature over the past 50-100 years (Lachenbruch et al., 1989; Balobaev, 1985; Taylor and Judge, 1985). A very clear departure from the long-term geothermal gradient has been observed at depth. Although the historical record cannot be recovered as a unique solution, a surface temperature record can be determined (with decreasing precision for older events). The records display evidence of permafrost disturbance, though the driving mechanism is not necessarily a simple relationship with climatic changes. Lachenbruch and Marshall (1986) concluded that the deviations were due to an increase of the surface temperature in the range of 2°-4°C during the last century or so. This coincides with the amelioration of global temperatures since about 1850, following the Little Ice Age.

2.3.2 Responses of permafrost to climatic changes

Since permafrost is a thermal condition, it is sensitive to changes in climate. Additionally, permafrost to a large extent is inherently unstable, since it exists so close to its melting point and frequently contains large amounts of excess ice. Most permafrost in the discontinuous zone is either relict, or in a delicate thermal balance with its environment. Many thousands of square kilometres of permafrost are within 1°-2°C of the melting point and are particularly vulnerable to climatic warming. The overall effect of the projected changes in climate will be to raise the mean annual surface temperature, which will result in a deeper active layer with the permafrost table receding until an equilibrium with the new surface temperature regime is established. The base of the permafrost would also rise, though at a much slower rate. If the progressive warming were great enough, then the permafrost could eventually disappear altogether, although many centuries could be required for a complete thaw. Of more immediate importance would be various rapid-onset effects in areas of thaw-sensitive permafrost (that for which the potential for thaw and subsidence are great, and which contain up to 80% volume of ice in the upper 5-10 m). Global warming could cause the upper layers (0-5 m) to experience accelerated thawing, probably resulting in the disappearance of permafrost - on the order of decades. At the lower latitude margins of the permafrost regions, climatic warming will induce thickening of the active layer in areas that continue to be underlaid by permafrost. An example of the fairly rapid response of permafrost to climatic warming is the changes in the boundary of continuous/discontinuous permafrost in the Mackenzie Valley of several hundreds of kilometres in the late 1800s-1940s due to a temperature rise of 3°C (MacKay, 1975).

Most responsive to changes in climate would be those portions nearest the surface and potentially serious impacts are associated with the melting of shallow ground ice. If ice-rich permafrost degrades, widespread terrain disturbance and instability will be likely, including thaw settlement (up to several metres) and ponding of surface water (associated with thermokarst), slope failures (landslides) and increased soil creep. The associated thickening of the active layer (the layer of ground subject to an annual regime of freezing and thawing) would lead to a decrease in the stability of the surface. Even in colder, continuous permafrost areas, increased ground temperatures could lead to similar conditions of terrain instability, although there may not be any major changes in areal distribution of the permafrost.

In practical terms, increased terrain instability would lead to major concerns for the integrity of roads, airfields, dams, reservoirs and structural foundations located in affected areas. Thickening of the active layer would subject foundations to continuing deformations as a result of thaw settlement. Decreases in the amount of ground ice present would lead to decreases in the mechanical strength of the associated soil as well as increases in permeability, both of which will have significant consequences for engineering and natural processes.

Slope failures and thermokarst features would have detrimental effects upon local vegetation and could lead to significant decreases in plant species numbers and loss of sensitive populations. In the long-term, degradation of permafrost would allow the growth of deeper rooted, broadleaved species and the establishment of denser forests of coniferous species (Zoltai and Pettapiece, 1973). Over hundreds or thousands of years, species better adapted to warmer air and ground temperatures will tend to advance to higher latitudes. As the extent of the tundra shrinks, northern species may become less abundant as others replace them, potentially leading to the loss of some of the more sensitive plant species and ecosystems.

Changes in wildlife are generally dominated by many factors other than permafrost (see Working Group II Report, Chapter 3). Degradation of permafrost and its effects on vegetation and forests, however, will influence wildlife through disruption of the terrain, changes in surface hydrology and food availability. It is likely that these changes could both enhance and diminish species variability and numbers (Harington, 1986). For example, native arctic species such as muskox, caribou and lemmings might suffer due to changes in climate and to their ecology. A northward shift of the forests would reduce tundra and barrenlands species. Changes in wetlands may affect nesting areas and migration routes for waterfowl and other birds, as well as populations of insects and other wildlife native to these regions through potential losses and gains (thermokarst) in wetland areas. The overall impact on wildlife due to the expected permafrost degradation would be difficult to assess, especially considering the transient nature and rate of the expected ecosystem changes and associated changes in food and habitat availability.

The response of permafrost to a change in the surface temperature is a function of both the initial condition (ground temperature profile), thermal properties, and other factors (ie nature of the surface temperature disturbance, ice content and local heat flow). On an annual basis, heat transferred into the permafrost during the thaw season is removed during the freeze season and a stable permafrost table is established. A disturbance (such as a climatic warming) which introduces more energy during the yearly cycle without a compensating heat removal will cause the permafrost to reach a new equilibrium at a lower depth or to disappear entirely. As permafrost at todays depths is still adjusting to climates of past millennia, contemporary climatic changes may require thousands of years to alter the bottom of permafrost (Lunardini, 1981).

The effects of climate on permafrost temperatures depends on the relationships between air temperature, ground surface temperature, and the ground thermal regime. Ground surface temperatures are determined by the interaction between climate and surface conditions, while ground temperatures respond to the surface climate according to the thermal properties of the ground and the energy flows, phase changes etc. An increase in summer precipitation and temperatures would greatly increase ground surface temperatures (Goodwin et al., 1984). Wide variations in ground thermal conditions can occur within small areas of uniform climate, although in areas of little vegetation or snow cover the linkage between air temperatures and ground temperatures is more direct. The range in ground thermal conditions typically observed between sites in close proximity can be equivalent climatically to several degrees of latitude.

Climate warming will alter the annual temperature range in the ground, temperatures will warm least in that part of the year in which the ground experiences significant phase change (spring and autumn). Increased soil temperatures as a result of climate warming will penetrate slowly in warm permafrost, since the temperature change requires the absorption of significant latent heat of fusion (the entire latent heat of fusion for the soil if it warms above zero).

Changes in the buffering action of the surface layer (snow cover, vegetation, the organic layer and the mineral soil) will also be an important factor in determining the impact of climatic changes on permafrost. For example, where organic material is present, the permafrost would probably not degrade as quickly as at other sites, especially when combined with the effects of a forest canopy. Suggested increases in the incidence and severity of forest fires induced by climatic changes would accelerate permafrost decay.

Any changes in the surface properties or hydrologic conditions (such as those brought about by ecosystem changes concomitant with a change in climate) will undoubtedly have an effect on microclimatic conditions and thus ground thermal conditions. As a result, once permafrost degradation is initiated, thaw settlement can result in radical changes in the surface energy balance and the effectiveness of the buffer layer, accelerating further degradation.

The removal, damage or compaction of surface vegetation, peat and soil associated with changes in land use or catastrophic events can alter the balance of surface energy transfers, especially the rate at which heat can enter the ground. In general, these changes will lead to an increase in the mean summer surface temperature accompanied by deeper thawing of the active layer (Brown, 1963; Mackay, 1970), though soils under a disturbed layer can also freeze more intensively in winter (Gavrilova, 1973, 1978, 1981). Clearing and construction associated with the Norman Wells, Canada, pipeline right-of-way has caused a 2°C temperature increase in mean annual ground surface temperature compared to the adjacent undisturbed areas. Areas of sporadic permafrost have disappeared in northern Alberta, Canada, as a result of clearing, ploughing and planting.

Changes in snow cover accumulation, as suggested under various climatic change scenarios or that may result from creation of barriers, structures and depressions, or changes in vegetation cover or wind patterns, can lead to significant warming or cooling of the ground. The erection of snow fences has been shown to have an immediate warming effect on ground temperatures, maintained even against natural cooling trends. Gavrilova (1973,1978,1981) has found that similar disturbances to the surface cover can have opposite effects on the ground thermal regime in different regions or with differing sub-surface materials. However, the effects of surface environmental changes are usually restricted in areal extent, whereas climatic change, in contrast, can affect extensive areas of permafrost.

2.3.2.1 Changes in permafrost distribution

Climatic oscillations have caused significant degradation of the permafrost in the past (Danilov et al., 1985). For example, the multilayered permafrost in West Siberia consists of a relict part near its bottom, relatively new permafrost at the top, and a thick unfrozen layer with positive temperatures near zero separating them. Canadian and Soviet work (MacKay, 1975; Baulin and Danilova, 1988) document the fact that the areal extent of permafrost has changed over very long time periods. There is recent evidence for both aggradation and degradation of permafrost with studies showing the southern margins in retreat (Thie, 1974; Mackay, 1975; Hunter, 1988).

The problem of predicting the influence of climatic change on the future distribution of permafrost can be treated by examining the relationships between permafrost and climatic parameters. An ideal method for predicting permafrost response would consider the effects of macroclimate, snow cover, soil thermal properties, substrate variability, vegetation, and terrain complexity. Although scale dependencies may prevent a detailed depiction of the effects of parameters with strong local variations, their influence may still be discernible in a generalised manner (Nelson, 1986).

Nelson and Outcalt (1987) suggest that a 'frost number' based on frost/thaw depth ratio may be applied to the general problem of permafrost distribution and climatic changes. Stuart (1985) has demonstrated the validity of this approach. This index considers several important variables that influence permafrost, and can be computed using climate data that are widely available. Moreover, the index can be displayed in the form of readily interprétable maps.

The frost number uses freezing and thawing degree-day sums, or alternatively, freezing and thawing depths in the soil to régionalise permafrost on the basis of its continuity or discontinuity. Snow density, thickness, and duration, as well as soil thermal properties, are considered in the more elaborate variant of the model. Although vegetation has not been treated in any regional application to date, its effects could be taken into account in a generalised fashion through use of n-factor data (Lunardini, 1978). The limitations imposed by scale considerations on the inclusion of such effects should be kept firmly in mind, however, particularly in light of the fact that the frost number was devised to show broad relations over areas of continental dimensions. The frost number is also somewhat limited in its applicability to short-term climatic changes, owing to its implicit assumption of stationarity.

The frost number methodology was applied to the problem of examining permafrost distribution, subject to the limitation noted above, induced by climate warming for both permafrost regions and those with deep annual freezing within the territory of the USSR. For these purposes, the scenario of regional climatic changes derived from palaeo-based reconstructions was used (Budyko and Izrael, 1987).

The greatest changes in soil thermal regime are expected in the northern continental regions, whereas the near-coastal regions changes are not expected to be as pronounced. Under a 2°C global warming scenario (by the 2020s), active-layer thickening of 10% can be expected in continental situations exemplified by central Siberia, but only 5% in regions subject to oceanic influence (eg Kamchatka). Climatic changes will also increase the duration of summer, which may be very important for regions with deep seasonal freezing. Such changes may have a profound effect on enterprises such as agriculture.

Estimates such as those given above are valid only for the near-surface layer, as only seasonal freezing and thawing are considered. Changes in the thermal regime deep in the permafrost can be differentiated into two groups vis-a-vis global warming: i) a relatively fast reaction in regions where global warming fails to produce an inter-permafrost talik (a layer of thawed soil); and ii) slow thermal evolution when large amounts of heat are expended on phase changes in warm permafrost. These topics were addressed by Anisimov (1989a; 1989b), who employed a non-stationary model of heat and water transport in a stratified medium in conjunction with the climatic palaeo-based reconstruction method to estimate changes in the extent of permafrost in the territory of the USSR. The results of that study suggest up to a 10% areal reduction of the extent of continuous permafrost in the USSR over a 50-year period, given a 2°C temperature increase (Figure 7.3). Talik is expected to form between the top of the permafrost and the bottom of the active layer with the thickness of this melted layer increasing with time.

Palaeo-based reconstructions of the potential impact of the projected changes in climate have been developed using the Holocene climatic optimum (5000-6000 years bp) and the climatic optimum of the recent interglacial (125 000 years bp) as probable analogues of warming by 1°C and 2°C respectively (Velichko et al., 1990). This analysis suggests that significant changes can be expected in the areas from which the presence of permafrost retreat towards the poles. Permafrost degradation is expected with an associated increase in the thickness of the active layer. The southern contemporary boundary of permafrost could shift northward in those areas where the permafrost thickness is currently less than 25 m.

The actual impacts of the projected changes in climate are complicated by the influence of an expected increase in snow cover in much of the current areas containing permafrost. Recent observations of the response of permafrost to increase in temperature and snow cover (northern portion of Western Siberia during the 1940s) suggest that the maximum potential response of the permafrost during the next 2-3 decades to the projected climatic change may be one-half of that suggested by equilibrium analyses due to the influence of increased snow cover.

Under global warming of 1°C the most significant changes within the USSR are proposed for the southernmost portions of the permafrost with the boundary of the climatic zone which supports permafrost shifting northward and northeastward by 200-300 km. This will significantly expand the area of relict permafrost in western Siberia and the Pechora Valley. The boundary of the climatic zone which supports continuous permafrost will also recede approximately the same distance; however, in those areas where the ground temperatures are currently -5°C to -7°C continuous permafrost will be preserved. The thickness of the active layer (in loamy soils) is expected to increase by no more than 0.5 m.

A 2°C global warming (projected for 2020s) will shift the southern boundary of the climatic zone which supports permafrost over most of Siberia north and north eastward by no less than 500-700 km from its current position. In the north of Eastern Europe only relict permafrost will remain. The climatic zone supporting continuous permafrost will disappear from Western Siberia and will be restricted to north of the Arctic Circle in Eastern Siberia. The depth of the active layer (in loamy soils) is expected to increase by nearly 1 m (Figure 7.4a).

Within Canada under a 1°C and 2°C increase in global temperature, responses within permafrost similar in magnitude to those for the USSR are suggested (Velichko et al., 1990). The southern boundary of the climatic zone supporting permafrost is expected to move poleward by approximately 200 km and 700 km, respectively. Expected increases in the depth of the active layer of 0.5 m and 1 m, respectively, are similar to those proposed for the USSR. Permafrost will be preserved at latitudes of 66°-68° N where low mean ground temperatures of -5°C to -6°C will persist even under a global temperature increase of 2°C (Figure 7.4b).

Goodwin et al. (1984) examined the impacts of 3°C and 6°C increases in temperature at two locations within Alaska: Barrow (continuous permafrost) and Fairbanks (discontinuous permafrost). At Barrow, primarily as a result of higher summer temperatures, the thickness of the active layer increased 41% and 71% respectively. At Fairbanks, the depth of the active layer increased 11% and 24% respectively with winter temperature apparently playing the dominant roles.

Osterkamp (1984a; 1984b) discussed quantitatively the potential impact of climatic changes on permafrost and the time scales involved for various regions of Alaska. Under a ground temperature increase of 3°C, a general warming is expected to occur in the continuous permafrost zone causing the permafrost to thaw at its base until it thins and a new equilibrium is reached (several thousand years). In the case of both continuous and discontinuous permafrost, thawing from the top and base may be expected. Generally, permafrost with a thickness of approximately 25 m is expected to completely thaw over about 200 years.

Projects developed in China (Ruqiu, 1990) suggest that over the next 10-20 years a 0.5°C increase in mean global temperature would result in a 5% decrease of the permafrost and that a 2.0°C increase would produce a 10-50% decrease. Under this latter scenario, major portions of the large and continuous areas of permafrost in China would no longer exist.

A mean annual warming of 2°C may have significant effects on the extent of permafrost ice on Mexico's higher peaks (Menchaca and Byrne, 1990). Disappearance of existing ice fields, although currently not larger than 5 km, would have important consequences for the hydrology and ecology of local streams and perhaps local climatic conditions (eg cold air drainage).

2.3.2.2 Implications of permafrost degradation

Global warming could result in an increase in the depth of maximum thaw (permafrost table) and a general warming of some thickness of the permafrost, even if the permafrost itself does not thaw. However, if the global warming also disturbs the buffer layer (eg increase in snow depth or duration) the effect on the active layer may not be reliably predictable. The active layer is the zone where many damaging phenomena such as frost heave and thaw settlement are most significant. If the active layer increases in thickness, it will probably compromise the foundation designs of existing engineering systems founded on permafrost and can cause mechanical disruption of roots. Active layer growth will also mean an increase in the temperature of the remaining permafrost with the attendant operational difficulties associated with the decreased strength of warm permafrost.

An increase in the temperature of frozen ground will result in changes in mechanical properties, in particular soil strength and deformation characteristics. This will adversely affect the stability of slopes. Natural processes such as slumping, solifluction, and icing (ie sheet of ice on the ground surface as the result of groundwater seepage) can all be expected to accelerate. In mountainous areas such as Tjan Shan and Pamir in Central Asia, the thawing of moraines and stone glaciers could destroy structures (eg communication towers) located on slopes. The adverse effects of such phenomena are abundantly in evidence and give ample warning of what to expect in the permafrost regions should the expected global warming occur.

A critical feature of some permafrost is the presence of massive ice (which may be detected and mapped using ground probing radar). When melted, the areas which have these deposits could experience land subsidence, shoreline retreat, and lake formation, directly related to the amount of ground ice and its thaw rate (Schur, 1974; Grigorian et al., 1984). The failure of ice-rich riverbanks and slopes (Lawson, 1983) would be accelerated by general permafrost degradation. Although the interaction between permafrost and bank erosion is not well understood, it seems likely that in the short term thawing permafrost would aggravate streambank erosion. In the long term this erosion will not be significant in areas where the permafrost has disappeared.

Soil erosion can be acute when the soil is finely textured and there are high quantities of melting ground ice (Linell and Tedrow, 1981). Where slopes are steep, solifluction and mass-wasting can be very significant erosion mechanisms. Degrading permafrost in ice-rich areas will increase natural erosion.

In regions where the top of the permafrost (permafrost table) is lowered as a result of thawing, available soil moisture may eventually be decreased. In some areas, water is kept near the surface by a relatively impermeable layer of ice provided by the permafrost table. Existing vegetation can tap this moisture, with roots extending throughout the active layer. With the degradation of the permafrost, the permafrost table will retreat to lower depths in the soil or, may even disappear altogether. Water may no longer be trapped near the surface, reducing the amount of moisture available to the overlying vegetation. The forest (taiga) in Central Yakutia (Siberia), for example may become more desert-like if the permafrost table lowers. Serious drying could occur in areas of plateau permafrost in China, leading to a degradation of grassy marshland. In some portions of the plateau permafrost a desert-like low-temperature plateau area could develop and existing pasture land areas could decrease.

Permafrost is a product of climate, but it in turn influences climatic conditions through the heat and water balance near the surface, in air and in soils. Frozen soils absorb a great amount of heat during active layer development (thaw) in summer. Frozen soils also retain large amounts of moisture. Deepening of the active layer and increase in soil temperature will bring large volumes of water-bearing soils into the local water and energy balances in the short term. Increased evaporation may alter the areal, temporal aspects and types of cloud cover which could significantly effect the overall energy balance.

2.3.3 *Gas hydrates and methane*

Gas hydrates can form in places where gas and water exist under high pressure and low temperatures. In the case of permafrost, these conditions can exist within and beneath the permafrost and solid crystals of gas hydrates can be found. Although gas hydrates were observed in Siberia in the early part of the 20th century, only in recent years has active interest been focused on whether they are widespread in permafrost regions. Because of their potential impact on climate warming it is important to consider where such deposits may exist and how they may be affected by the projected changes in climate.

Evidence exists that degradation of permafrost as a result of the projected GHG-induced changes in climate will result in an increase in atmosphere. Degradation of permafrost will subject previously frozen biological material to rapid oxidation and large scale release of methane, and to a lesser extent CO_2 (Billings et al., 1982) into the atmosphere. In addition, significant quantities of methane within gas hydrates (Kvenvolden, 1988) that are trapped within and beneath permafrost will provide large amounts of this greenhouse gas to the atmosphere as degradation proceeds. Of the various sources of methane on the earth, the most uncertain is that connected with gas-hydrate formations and their degradation.

In the USSR, gas hydrates have been found in the Messoyakha gas field of western Siberia (Makogon et al., 1972), Timan-Pechora province, the eastern Siberia craton, and in the northeast and Kamchatka areas (Cherskiy et al., 1985). In the North American Arctic, hydrates are known in the Mackenzie Delta, the Sverdrup Basin, the Arctic Platform and the Arctic Islands (Judge, 1982), and in the North Slope of Alaska (Collett, 1983). A summary of the gas hydrate estimates of various authors (Table 7.4) was adapted from the Potential Gas Committee (1981).

Table 7.4 Estimates of methane hydrate resources within permafrost regions (adapted from Potential Gas Committee, 1981)

Volume m^3	Mass GT (10^{15}g)	Reference
	OCEANIC	
3.1×10^{15}	1.7×10^3	McIver (1981)
$5\text{-}25 \times 10^{15}$	8.0×10^3	Trofimuk et al. (1977)
7.6×10^{18}	4.1×10^6	Dobrynin and Koratajev (1981)
	CONTINENTAL	
3.1×10^{13}	1.7×10^1	McIver (1981)
5.7×10^{13}	3.1×10^1	Trofimuk et al. (1977)
3.4×10^{16}	1.8×10^4	Dobrynin et al. (1981)
	4.0×10^2	MacDonald (1980)

Estimates of annual methane release from hydrates over periods of several decades varies between 5 Tg/year (Cicerone and Oremland, 1988) and 160 Tg/year (Kvenvolden, 1988), the largest component in all cases being derived from areas of offshore permafrost. Hydrates contained in terrestrial permafrost are considered to be effectively isolated from warming, and would require centuries for temperature changes to affect them in any appreciable way.

The contribution of methane derived from gas hydrates may lead to an additional 0.4°C increase in global temperature by the 2020s and 0.6-0.7°C by middle of the 21st century, when atmospheric methane concentrations are expected to be twice those in the pre-industrial period. There is reason to expect that the positive feedback between climate and methane hydrates in permafrost may be even stronger than this. Owing to photochemical reactions between minor atmospheric constituents, an increase in the concentration of atmospheric methane will cause an increase in its lifetime in the atmosphere, and the greenhouse effect produced by this gas could therefore be higher.

The qualitative analysis presented above demonstrates that hydrate-climate interactions will indeed result in positive feedback and intensification of the greenhouse effect within the atmospheric system; owing to the many uncertainties and quantitative disagreements between authors, only a sign and an order of magnitude for this effect may be stated with confidence now. Further investigations are needed urgently to refine this.

2.4 Seasonally frozen ground

Seasonally frozen ground occurs in those areas where the ground temperatures drop below 0°C only during some portion of the year (ie some fraction of the winter months). Frost penetrates the ground from the surface as the energy balance lowers ground surface temperatures to below freezing. The depth of frost penetration is controlled by several factors, primarily air temperature, the nature of the surface cover, water content in the soil and the thermal characteristics of the soil and snow cover. To a large extent, the physics associated with seasonally frozen ground are analogous to aggradation and degradation of permafrost with the major difference being that, in the case of permafrost, the ice persists throughout the year. The role of the 'buffer' layer in the dynamics of the frozen ground, however, is similar.

Global warming will affect the areal distribution of seasonally frozen ground and the depth of frost penetration. With warming and if other factors are essentially unchanged, the area experiencing seasonally frozen ground will be reduced and, for those areas where the ground will still experience annual freezing, the depth of penetration will decrease. As in the case of permafrost, changes to the buffer layer (eg snow cover and vegetation) as a result of climatic changes could influence the responses in some locations due to the net effect on the local surface energy budget.

The impact of the projected changes in climate on frost penetration can be illustrated using empirical estimates based on degree days below 0°C. Calculations shows that for two locations in Canada, one a relatively cold location (Calgary, Alberta) and the other a more temperate location (Toronto, Ontario), frost penetration will be reduced significantly by 50-60% and 75-85% respectively as a result of an increase of 6°C in the mean annual air temperature (Brown, 1964; DOT, 1968).

Regions experiencing seasonally frozen ground undergo many of the same detrimental effects noted for the permafrost zones and commonly support large populations, especially in North America. Reduction of the area experiencing seasonally frozen ground or in the depth of frost penetration would have significant positive ramifications especially for the agriculture and construction industry.

3 Socioeconomic consequences

3.1 Seasonal snow cover

Despite the transient nature of seasonal snow cover, it plays an important role in the earth-atmosphere system both in a biophysical and a socioeconomic sense. Seasonal snow cover (along with mountain glaciers) is a vital water resource for irrigation, hydroelectric power generation, agriculture and potable water. There will be detectable changes in river flow regimes from the projected changes in snowfall and melt patterns. This would result in increased winter runoff in some regions owing to higher temperatures and a greater percentage of precipitation falling as rain. Less water would be available during the summer months in those regions which rely on snowmelt. These suggested changes could decrease the annual amplitude of river discharges with water management benefiting as the demand for regulated storage decreases (Eriksson, 1989).

This change in runoff regime will have repercussions for hydroelectric power generation. Hydro projects such as those in eastern Canada at La Grande (Quebec) and Churchill Falls (Labrador) which fill their headponds from the snowmelt water accumulated over the eight-month subarctic winter will be significantly affected by changes in snow cover and melt. Particularly sensitive are those areas for which snow melt supplies a major proportion of the water resources. This includes areas of the Alps and Carpathians of Western Europe, the Altai and Tjan-Shan Mountains of Central Asia, the southern Andes in Argentina and Chile as well as in numerous parts of the Western Cordillera of the US, to cite a few examples.

Computer simulations show desiccation of large areas of the mid-latitude agriculturally productive areas in the northern hemisphere (Schlesinger and Mitchell, 1985). This summer drying is, in part, due to the earlier spring melting of the seasonal snowpack. This has implications for many regions of the world adjacent to snow-rich mountain water supplies that recharge major rivers and groundwater reservoirs. For example the South Saskatchewan and North Saskatchewan Rivers in the Canadian Prairies maintain strong base flows even in drought years because their principal sources are in the Rocky Mountains. Similarly the Syr Dar'ya and the Amu Dar'ya Rivers passing through dry regions of the Central Asian republics of the USSR to the Aral Sea are fed from snow supplies in the Hindu Kush and neighbouring mountain systems.

As a consequence of projected changes in snow cover in New Zealand, the seasonal flow of rivers would change markedly, with major ones like the Clutha and Waitaki having 40% more flow in winter and 13% less flow in summer, although the latter could be further augmented by meltwater from diminishing glaciers. Annual runoff could increase by 14%. On smaller mountain streams, vital for local irrigation, the lower snow storage will probably lead to decreased summer flows when some will dry up.

Survival of over-wintering agricultural crops such as alfalfa, winter wheat and perennial forage legumes in cold climates is linked to whether or not a persistent snow cover exists during the winter months. Periods with warm temperatures and rainfall which melt existing snow cover and result in a dehardening of over-wintering crops commonly result in significant losses (up to 30-40% on average for forage legumes and winter cereals in the Canadian Maritime Provinces, Suzuki, 1989). Changes in the frequency of these warm air intrusions would place these crops in a vulnerable position should the temperatures subsequently drop quickly below freezing. In addition, because of the bare ground with a freeze-thaw cycle, soil heaving and soil cracking could be extensive, jeopardising tap root crops such as alfalfa and exposing underground tissue.

Seasonal snow cover is vital for winter tourism and recreation. In southern Quebec, Canada, it has been estimated that as a result of the GHG-induced climatic changes the number of days suitable for skiing would decrease by half or more, representing losses of tens of millions of dollars annually to the economy. The situation in the south Georgian Bay area of Ontario could be worse with the virtual elimination of a $50 million annual downhill ski industry with impacts on associated suppliers.

Of particular concern to winter tourism is the economic consequences of a change in the seasonal distribution of snow cover. Should the start of the snow cover season be delayed until late December or January, winter tourism (eg skiing industry) would lose one of its most profitable periods (ie Christmas and New Year).

Tourism will be both positively and negatively effected by suggested changes in snow cover (Chinn, 1989). Less spectacular glacial and winter scenery may decrease the number of tourists; however, a more agreeable climate and easier access may encourage touring and hiking activities as the environment would be less demanding.

Changes in seasonal snow cover will have repercussions with respect to snow removal costs and vehicular accidents. At Toronto, Ontario (Canada), a comparison was made between 1981-82, a near normal snowfall winter, and the succeeding year 1982-83 which received 52% of normal snowfall (Rowe, 1984). Snow removal costs on roads, at the airport and at public buildings were reduced to near 60% during the more open winter. Costs of vehicle accidents attributed to weather were reduced to 55% of that incurred during the snowy winter.

Avalanche activity is one type of catastrophic event that may be affected as a result of climatic changes and potential changes in snow pack quantity and quality. Avalanche control is an expensive proposition, although justifiable based on the costs associated with lack of control.

The fact that avalanches are also influenced by terrain and weather conditions adds complexity to the relationship between climate and avalanche activity. Data analysis of avalanches for the period 1800 to 1985 does not show any temporal trends (Fohn, 1989). An analysis of the period from 1885 to 1985 suggests that avalanche activity is associated with nine specific weather types. Projections of the frequency of these specific weather types under conditions of climate warming are required in order to assess effects on avalanche activity.

Rogers' Pass in the Columbian Mountains of the Canadian Rockies averages approximately 38 major avalanches (more than 0.3 m of snow on the road) per winter. In addition to operational costs of monitoring and control (approximately $200,000 annually in Banff National Park), these events can result in increased costs through clean-up related expenses and costs associated with re-routing or delays for transportation (road and railway).

3.2 Glaciers and ice sheets

In many parts of the world glacier runoff makes a significant contribution to the total water resource. Glaciers contain an enormous reserve of water equivalent to precipitation over the entire globe for about 60 years. Possible effects of climatic changes on availability of glacier runoff water should be taken into account in long-term water resource planning. The disappearance of 8.3 km^3 of water over the next 70 years as a result of glacial retreat in Austria (Kuhn, 1989) will contribute to the runoff of the Danube, Drau, and Rhine Rivers to the extent equivalent to only one 100 mm rainfall evenly spread over the entire country, or little more than 1 mm/year. For example, glacier retreat in the Susitna River basin - Alaska, where a major hydroelectric faculty has been under consideration - has been large, and may increase as a result of climate warming. The availability of glacially derived water in the future needs to be considered.

In New Zealand over 70% of the electricity is produced by hydroelectric generation (Fitzharris, 1989). Under present conditions glaciers contribute to about 10% of the summertime flow in certain western rivers. Models indicate that a 3°C increase in mean annual temperature could result in a 10% increase in electricity production on an annual basis and would reduce water storage requirements. Changes in water management strategies would be required.

The projected decrease in glacial coverage could increase the incidence of debris flows (Zimmermann and Haeberli, 1989). Uncovered debris masses on steep slopes have been exposed to erosive processes during the recent retreat of glaciers (Church and Ryder, 1972; Quilty, 1989). This debris has been responsible for the partial and complete burial of structures, traffic routes and vegetation and is commonly deposited in rivers obstructing their flows and increasing sediment loads. Increases in the amount of exposed debris are likely as glaciers retreat under the influence of projected climatic changes, thereby increasing the probability of debris flows.

Research in Scandinavia suggests that projected temperature increases will cause enhanced glacier retreat and increased discharge into rivers which carry glacier meltwater (Karlen, 1989). Severe flooding of these river basins is not expected if the mean summer temperature increase is of the order of 1.6°C, however, if the mean summer temperature is increased by 5.5°C over a relatively short period of time, heavy flooding could occur.

3.3 Permafrost

Communities at high latitudes have adapted with varying degrees of success to the presence of permafrost. The effects of permafrost warming on these communities will depend on the relationships between the natural environment (including permafrost) and the various structures and facilities that make up the community. Although many anticipated impacts of permafrost degradation are negative (including the possible relocation of whole communities), positive impacts are also foreseen, especially in the long term after the near surface layers have achieved some measure of equilibrium with the climate.

Construction on permafrost has been dealt with by building on its strengths and reducing its weaknesses. Heated structures in permafrost are usually designed using one of four approaches:

i) Disregard the thermal regime of underlying permafrost, and apply conventional techniques of temperate regions. This assumes that thawing of the permafrost will have no adverse effect on the structure. This is a risky design approach on thaw-unstable permafrost for all but small or short-lived structures. Where appropriate, this approach would be unaffected by climatic change.

ii) Thaw permafrost before construction. This approach is expensive and not used widely, except in the mining industry in Alaska (Sanger, 1969) and Russia (Bakakin and Zelenin, 1966). The procedure is limited to the discontinuous permafrost regions. It is possible that climatic warming may eventually lead to more widespread use of this design technique.

iii) Allow for thaw during the construction and operation of the structure. In the discontinuous permafrost zone where consolidation and thaw must be expected the permafrost may, under very special conditions be allowed to thaw during and after construction. The method should be used only where the foundation materials are thaw-stable or where expedient or short-term construction is involved. Generally, the design must allow for differential thaw and settlement. Although the Soviet Building Code (1960) lists the depth and rate of thaw allowable, the prediction of differential settlement is so unreliable that the entire procedure must be considered risky. Climatic warming would add new uncertainties.

iv) Maintain the permafrost in a frozen state. One of the most common design techniques presently used is to prevent thawing of the permafrost by maintaining the permafrost table and temperature for the life of the structure. This technique, which is vital in continuous permafrost, is now widely used in Canada, USSR and the US. Climatic change would cause problems for those structures founded on permafrost which would not be sustained under a new climatic regime.

Existing foundations designed on the principle that the ground remains frozen for the life of the structure will require modification. Pile foundations in permafrost rely not only on the ground being frozen but the bearing capacity of individual piles is a direct function of the temperature of the frozen ground. Permafrost can lose more than half of its strength when warming close to the freezing point without thawing; actual thaw can reduce its bearing capacity to practically zero. Thickening of the active layer will mean an increase in the length of pile affected by seasonal frost action. Thus, any changes that can produce a warming of the permafrost can have a significant effect on such piles, within the life span of the structure. Structures will have to be redesigned to accommodate such warming where possible, or resort to refrigeration systems to maintain freezing temperatures.

Permafrost warming or degradation, increased depth of seasonal freezing and thawing and associated increases in frost heave forces (Esch and Osterkamp, 1990) will result in an increase in the maintenance requirements of facilities founded on permafrost. When maintenance costs become excessive it may be necessary to retrofit existing facilities for economic reasons. Such remedial measures could include presently available methods such as supplemental freezing of the foundation materials, stiffening or replacement of the supporting structure, adding earth materials, insulating materials etc. Each type of facility will require retrofitting schemes tailored to preserve its function. Retrofitting and maintenance programs will require the use of existing techniques and the development of new maintenance methods.

Bridges, buildings and utilities founded in thaw-sensitive permafrost would experience an increased rate of settlement with any increase in permafrost temperature, due primarily to the creep of the frozen soils. The rates would be greatest in fine grained (silt or clay) ice-rich soils. Facilities on thaw-stable materials would be affected minimally by a rise in temperature. However, many structures are located on ice-rich permafrost soils and most utility lines (water, sewer, steam etc) traverse ice-rich soils and even ice wedges. The thawing of this permafrost would result in large total and differential settlements. Even minor settlement can render doors, windows and other structural features essentially useless. Differential settlements would cause large internal stresses in the structure which could result in large distortions or even collapse. Utility lines could rupture where large differential settlements occur. These lines are particularly vulnerable where they enter or approach a structure undergoing significant settlement or where they traverse thaw-sensitive slopes. Thawing sensitive permafrost slopes could break portions of the lines away from portions founded on the stable soils or bedrock.

Monitoring programs will be needed in order to avert property damage, possible loss of life, and environmental degradation. Observations of soil temperature as well as of the movements of the structure and the surrounding earth would be required. The results of the observational program should provide guidance for instituting remedial measures that would minimise damage and avoid loss of life.

Monitoring of sensitive structures during the period of transition from permafrost to non-permafrost or for those structures not designed to adapt to degradation of the permafrost as a result of climatic changes will be expensive. For example, improper installation of wooden piles for a building in Fort Franklin, Northwest Territories in Canada (1985) necessitated introduction of a monthly monitoring program, which cost $120,000 over a two-year period.

Existing water-retaining structures founded on permafrost and subjected to an increase in temperature will suffer two serious consequences. First, the risk of water seepage through the foundation will be increased due to thaw in the foundation (as a result of the altered heat balance between the permafrost and the reservoir water), allowing seepage beneath the dam. Heat transported by the flowing water will accelerate thaw, exacerbating the seepage problem. Loss of water can have serious economic consequences where the water is being stored for human consumption or for use in industrial processes. Second, if the foundation materials are thaw sensitive, a catastrophic failure could occur owing to the reduction in strength when the frozen materials are thawed. The failure of dams retaining water could result in the loss of life and property downstream in addition to the economic loss of the dam and reservoir. To guard against the failure of a dam, extensive monitoring of dam and ground temperatures will be required, as well as measurements of seepage and ground movements. The natural earth slopes surrounding the reservoir would require monitoring for movement and temperature changes as well.

Current mining projects in areas of thaw-stable permafrost would be unaffected by permafrost degradation. Mines in thaw-sensitive areas, such as the Polaris mine near Resolute (Canada) have been designed to take advantage of the ice-rich permafrost (Giegerich, 1988), and degradation could create major problems there. In the Svalbard, Norway area there are currently no water problems in the mines due to the depth of the permafrost (200-300 m), although there is water under the glaciers (taliks) (Liest0l, 1976).

Mines such as Red Dog in Alaska, developed in ice-rich and warm permafrost regions, experience significant engineering problems related to stability and leaching (Giegerich, 1988). Permafrost degradation could only increase these problems over the short term. In the Isfjorden, Norway area, increased temperatures may affect the permafrost and create problems for mining only in the long term as thawing would take more than 100 years. In general, though, mining tends to occur in dry permafrost regions, and the melting of ground ice would not be significant (McKay and Baker, 1986). The release of methane from thawing permafrost could possibly be a health and safety hazard due to its poisonous and explosive nature.

Several changes are predictable as climatic changes influence the frozen ground in and around mine sites. The first change, while not a change in permafrost, will have significant effects on any mine which depends upon winter roads for supplies and back haul of product or other bulky materials. The snow road season will be shortened and the cost effectiveness will diminish. Conversely, increased precipitation as snow will ease the building of winter roads in areas where snow is presently in short supply. The Lupin Mine of Echo Bay Mines measures its savings from using winter roads in the millions of dollars each year.

The mining, blasting and handling characteristics of unfrozen ore are better than those of frozen ore. It is difficult to imagine, however, that climatic changes would have economically measurable effects when the duration of any one mine is considered and the more immediate thermal effects of shipping, blasting and moving ore are contemplated.

Of greater significance is the potential stability of mining structures which may persist beyond the economic life of the mine. These include waste dumps, tailings dams and water diversion channels. The stability of any or all such structures could diminish with increasing ground temperatures particularly if coupled with increased precipitation and runoff during the spring freshet. Increased precipitation plus increased ground water from the thickened active layer would increase costs of water management in open pit mines. In addition, the tailings pond management costs would increase as additional water handling and management would be required.

The complex subject of acid mine drainage in a permafrost environment could be affected by thermal and precipitation changes. More water from precipitation or permafrost degradation or both would increase the probability of acid generation at acidic mine sites. To the extent that receiving waters would have increased flow from non-acidic environments, however, the changes could be neutralised. Any increase in acidity would increase treatment costs.

In summary, the changes to the socioeconomic setting for surface mining would be measurable in several different ways but whether the net change would be positive or negative would depend upon local conditions and the degree of thermal change at any one mining operation.

Existing underground storage cavities and rooms in permafrost soils would be subject to accelerated closure due to creep of the frozen soil when warming occurs. If the temperature rises above the melting point of the permafrost, the underground openings would most likely collapse. The stability of the openings in the thawed soil would depend upon the type of soil (clay, silt, sand or gravel) and its thawed strength. The rate of closure of an opening in permafrost increases with temperature, moisture content (ice and unfrozen water in permafrost), the magnitude of the applied stress, and the dimensions of the unsupported opening. Local meat cellars in native villages may flood with increased precipitation and thaw.

Solid waste disposed of in a sanitary landfill site on permafrost subsequently freezes, so that decomposition occurs only slowly over the summer periods. The near-impermeability of permafrost ensures the isolation of leachate from local groundwater. Permafrost degradation could create a health risk at existing waste-disposal sites due to leaching and subsequent contamination of groundwater where the groundwater is no longer isolated from leachate by permafrost. Most governments will find it necessary to prohibit the practice of land application of liquid waste and to require that previously disposed toxic wastes be removed from areas where permafrost is degrading.

Some of the more important implications of changes in permafrost are found in transportation networks. The development of thermokarst ponds and the thawing of ice wedges and changes in patterned ground upon warming of permafrost would reduce the accessibility of many areas. There would be negative impacts on many existing road and railroad networks and airstrips. In addition, permafrost terrain is particularly sensitive to vehicular traffic, which can alter the surface and may induce thermokarst features or alter vegetative growth (Richard and Brown, 1974). In the short term, the sensitivity of natural surfaces would probably increase. This problem will eventually disappear in areas where permafrost degrades completely.

Long linear structures such as highways, airfields, transmission lines and pipelines must deal with a variety of design and construction conditions in that they traverse nearly all types of permafrost and non-permafrost conditions. An increase in the average annual temperature would cause the depth of seasonal thawing to increase to greater depths near these fadlities since much of the insulating vegetation has been removed from these areas during the construction of the facilities.

In the areas where the soils consolidate upon thawing, transport facilities could experience uneven settlements, as well as lateral movements at locations where the facility traverses sloping terrain. Conditions would be aggravated where drainage systems are disrupted by earth movements. If the drainage system were left uncorrected, water could pond near the facility and also run uncontrolled in the vicinity causing erosion and increased subsidence near and within the facility. Pavements would undoubtedly be fractured and the traffic supporting surface could become rough enough to be unusable if uncorrected. The possible risk of pipeline rupture and the accompanying environmental degradation would be increased in areas where the pipeline depends upon permafrost for support. As a result, the amount of maintenance required to keep these types of facilities operational would increase significantly. In many locations where thaw-sensitive soil is traversed it may be necessary to relocate airfields, highways and pipelines. In the case of either a hot or a chilled pipeline, it may be necessary to change operational procedures.

Some examples of the costs associated with repair and retrofitting of these types of structures are indicated by the following.

i) Electrical power transmission line extending 900 km from Saskatchewan to Nelson River area through the discontinuous permafrost zone south of Winnipeg, Manitoba in Canada. By 1974 the effects of frost action had necessitated repairs to the foundations of transmission towers totalling $2 million (1974). Power outages on the line imposed another $20,000 an hour and had an immense economic and social impact on corporate and domestic consumers.

ii) An unusually warm summer in 1989 caused major thaw settlement of the portion of the Deadhorse, Alaska, runway. Costs for remedial work on the runway is estimated to reach $440,000 and costs to rebuild the runway to overcome current thaw settlement problems is estimated at $6-8 million.

iii) Maintenance for roads on unstable ice-rich permafrost costs about $5000/year/mile more than roads on stable ground.

iv) The Northwest Territories in Canada has a total of 2000 km of all season roads and another 2000 km of winter roads and plans exist to build another 2000 km of all season roads. Construction costs are estimated at $200,000 to $300,000/km within the Mackenzie Lowland Area and $450,000 to $600,000 in the Precambrian Shield Area. It is estimated that designing to include the effects of the projected climatic changes will double these costs.

v) Alaska has 2300 miles of road of which 60% are in relatively warm discontinuous permafrost terrain. In recent years, 98 miles of highway have had chronic permafrost thaw settlement problems requiring frequent patching and levelling efforts while an estimated 340 additional miles will require eventual reconstruction to re-level sags, dips and spreading cracks at a cost of $150,000 to $200,000/mile. Repairs to 100 m of the Dempster Highway, Northwest Territories, where a large ice wedge thawed and a truck fell into the hole, killing the driver, cost $100,000 in engineering studies and $150,000 in repair work.

At present there is very little agriculture in northern high latitudes, although farming can be of significant local importance. The controlling factors on agriculture are many, and include climate and soil properties. Soil temperatures are critical, and summer values of less than 8-11°C prohibit agricultural crops. Much of the heat entering the ground in permafrost is required for thawing, thus keeping ground temperatures low. Linell and Tedrow (1981) conclude that agriculture on permafrost is usually not feasible, with the exception of greenhouse- or livestock-based agriculture. Agricultural prospects are limited for a variety of reasons, of which permafrost is only one and not the most significant. Studies reported by Dinkel (1984) suggest, however, that in some areas only slight increases in air temperature would result in greatly improved crop potential at the latitudes of Alaska.

Warming permafrost would benefit crop development by increasing active layer thickness and water availability, although degrading permafrost in ice-rich areas will probably increase natural erosion. Permafrost recession below the active layer would eventually allow summer active layer temperatures to rise more than at present, but reduce moisture availability. Warmer soil temperatures would extend the crop growing season.

Thermokarst features are favourable for crops in moisture-deficient environments. These depressions tend to have a more favourable moisture regime for crop growth than higher areas, in part because they tend to accumulate runoff. The melting ground ice creating the depression could act as a water resource for the crops. Thermokarst features are used to agricultural advantage, especially in Siberia and the Far East (Linell and Tedrow, 1981).

Hunting and trapping are a valuable food source for local northern communities, as well as a source of income. In 1982-83 they provided almost $3 million of income to the Northwest Territories (McKay and Baker, 1986). Hunting and trapping as well as forestry and agriculture would tend to be enhanced as permafrost degrades or disappears.

3.4 Seasonally frozen ground

Large portions of the world's population live in areas which experience seasonal frost. Decreases in the extent of areas experiencing seasonally frozen ground, and in the depth to which it penetrates, will be beneficial as costs of construction and maintenance of structures and the area experiencing frost heave and related crop damage are reduced.

Within the province of Ontario, Canada highways which experience seasonally frozen ground normally are repaired within 10 years of construction due to damages resulting from frost heave. The cost of this repair is estimated at $5000 -$10,000/km.

4 Future deliberations

Projected changes in climate will alter the distribution of seasonal snow cover, ice and permafrost. On a global scale, the areal extent of seasonal snow cover and permafrost will decrease as temperatures warm. Snow will move to higher latitudes and elevations and existing permafrost melting and boundaries retreating towards the poles. The global distribution of glaciers and ice sheets is also projected to decrease, however, their responses are complicated by projected increases in snowfall in some areas (eg over Greenland and Antarctica) which could contribute to the growth of some glacier and ice sheets. Secular climatic trends are clearly reserved in mass and temperature changes of glaciers and permafrost, which is mainly due to the slowness of heat diffusion and the retarding effect of latent heat exchange. Therefore, the analysis of permafrost temperature as a function of depth appears to yield a temporally integrated record of air temperature changes in the past.

The uncertainties in our understanding of the dynamics of seasonal snow cover, ice and permafrost are large. Our knowledge of snow accumulation rates, ice-shelf bottom melting rates and calving rates in Antarctica is significantly limited. Similarly, we have a poor knowledge of the ablation rates in Greenland and, even worse, calving rates there. Thus, we cannot say how these ice sheets will react until we know more about their basic dynamics.

Systematic monitoring of climatic and seasonal snow cover, ice and permafrost conditions at a regional scale is required to identify trends, to provide data necessary to increase our understanding of climate relationships and to assist in defining likely responses to changes in those conditions. Such data could be used to develop, refine and verify models of those relationships, and would also extend our knowledge of current distributions of seasonal snow cover, ice and permafrost and their dynamics.

Uncertainty exists on how proposed global changes will be reflected at the regional and local levels. This uncertainty stems in part from the lack of knowledge of climatic changes at these scales. Current generations of GCMs are not able to provide sufficient detail on how regional and local climates will change as a result of the projected global changes. The fact that precipitation changes are also uncertain even at the global scale increases the uncertainty associated with defining likely impacts. Palaeo-based reconstructions do not provide further refinement as the uncertainty associated with derived temperature and precipitation changes are at least as large as those associated with computer-generated scenarios.

Contributing to the uncertainty in the responses of seasonal snow cover, ice and permafrost is the relative limited understanding of their sensitivities and behaviour in relationship to climate and climatic changes. Furthermore, other influential factors such as vegetation and human activity are also sensitive to climatic changes. Therefore, a better understanding of the response of seasonal snow cover, ice and permafrost to climatic changes requires a comprehensive modelling approach.

Socioeconomic consequences of these impacts will be significant for those regions which depend on snow and ice for water resources, and their social and economic welfare (eg recreation and tourist industry). Proposed implications of permafrost degradation will adversely affect structures and facilities which have been designed assuming continuation of current permafrost conditions for their structural support and integrity. Response strategies to adapt to these changes which could include abandonment have both social and economic costs associated with them. Implications of changes in seasonal snow cover, ice and permafrost for ecosystem health and structure, and terrain characteristics could also be significant.

Understanding the socioeconomic consequences of proposed impacts on seasonal snow cover, ice and permafrost is in its infancy. In most cases the studies have not included a comprehensive approach and have not integrated appropriate representatives of sociological and economics communities. Continuing to limit the scope of these types of studies will limit our understanding of the full range of socioeconomic consequences.

Of particular importance in defining socioeconomic consequences is understanding how projected changes in seasonal snow cover, ice and permafrost could affect existing structures and how they could be modified to allow them to adapt to the proposed changes. In some cases, existing structures and facilities may have to be dismantled and new ones constructed whereas in others various degrees of retrofitting could be necessary. Retrofitting costs will need to be assessed and taken into consideration in construction costs for those structures and facilities that could experience a change during their lifetime. New design and construction standards that consider the proposed impacts of climatic changes and associated risks will need to be developed for structures and facilities that rely on, or are affected by, seasonal snow cover, ice and permafrost (eg hydroelectric dams, pipelines, urban infrastructure etc).

Seasonal snow cover, ice and permafrost are ideally suited for early detection of the effects on climatic changes. Despite the complicated nature of their responses, monitoring their behaviour could provide an effective indicator of climatic changes.

Increasing our understanding of the dynamics of seasonal snow cover, ice and permafrost, the factors that control them and the impacts of climatic changes and associated socioeconomic consequences are of upmost importance. Activities that should be undertaken to promote this include:

- Accurate projections of climatic changes, including seasonal effects, are required on a regional level. These are needed to assess the timing, duration, severity of climatic changes and the associated risks.

- Establishment or enhancement of integrated, systematic observation programs at the regional and local level and with cooperation internationally. These observation programs should be as comprehensive as possible and include coincident climatic and other (eg biological, pedological, geological etc) observations as required. Commensurate with these programs, is the need to promote research on the use of more efficient ground-based systems and remote sensing technologies (eg satellite measurements, laser altimetry, seismic technologies and ground-probing radar) and the interpretation of the data.

- In the case of permafrost, ground temperatures throughout the permafrost layer over long time periods and that are spatially representative are required to provide information on regional variations in permafrost responses to warming climate. An international network of deep (minimum of 100-200 m but preferably 1-2 km) boreholes on north-south transects should be established. The occurrence and distribution of gas hydrates found in and beneath permafrost need to be assessed to ascertain potential methane releases.

- A globally representative network of glacial and associated climatic observations for glaciers should be established and maintained. Mountain glaciers are among the clearest and most easily recognisable indicators of changes in climate (a direct link to summer temperatures). They 'record' both yearly variations and long-term changes and are relatively undisturbed by the direct action of humans. Mass balance studies are being carried out in different climatic zones and representative regions, however, significant gaps in the observation network exist mainly in the Southern Hemisphere and in the developing countries.

- Sensitive structures on permafrost such as pipelines, tailings dams, water retaining dykes and toxic waste sites should be monitored to check on the influences of climatic changes on their integrity. This information would assist in defining the risk of damage or catastrophic collapse of associated structures and, thus the need and type of remedial action necessary.

- The areal distribution of seasonal snow cover, ice and permafrost need to mapped on meaningful temporal and spatial scales to permit comparisons of changes in distribution under various climatic change scenarios. This should be done at both regional and global scales to allow broad application of the produced maps. In the case of permafrost, mapping criteria and internationally agreed operational definitions need to be established. In alpine basins the total volume of water stored in the seasonal snow pack is not monitored but, rather, measurement of snow depth and density at index points is relied on. It is not obvious that these will remain representative with climatic warming, and better methods of monitoring the spatial distribution of seasonal snow cover need to be developed.

- Regional and local analyses of the impacts of projected changes in climate on seasonal snow cover, ice and permafrost are required. These studies should be comprehensive including globally representativeness, direct and secondary impacts, feedback mechanisms, risk analyses, and associated socioeconomic consequences. These requirements can best be met through multidisciplinary impacts programs which include representatives from groups typically involved in impact studies along with botanists, economists, foresters, sociologists, zoologists etc. To mount these impact programs, national and international research funding agencies should be encouraged to support multidisciplinary impact studies. International coordination of these impact studies is essential and could be encouraged through cooperation between existing national and international agencies and associations.

- Dynamic models of the behaviour of seasonal snow cover, ice and permafrost which can address the implications of climatic changes should be developed and refined, especially those capable of operating at regional scales. To produce such models the relationships between the temperature of the air, precipitation, cloud cover and the behaviour of seasonal snow cover, ice and permafrost need to be more precisely defined. The role of other factors such as terrain, vegetation cover, human disturbances and, in the case of permafrost, the surface organic layer require particular attention.

- Research on appropriate design and construction standards for structures and facilities in areas which will experience changes in seasonal snow cover, ice and permafrost should be conducted. This includes defining standards for retrofitting and for new structures and facilities. This type of research could be undertaken by both private and public agencies and should be supported by appropriate funding agencies.

- The projected changes in the seasonal snow cover, ice and permafrost due to climatic changes should not be cause for neither alarm nor complacency. Those charged with planning and design responsibilities should be made aware of and sensitised to the probabilities of and quantitative uncertainties related to issues of climatic changes and proposed effects on seasonal snow cover, ice and permafrost. This necessitates the development and dissemination of appropriate education and information materials. Research results including impacts studies should also be made more readily available. Existing national and international agencies and associations should be encouraged to undertake this vital task.

Figure 7.1 Global distribution of permafrost

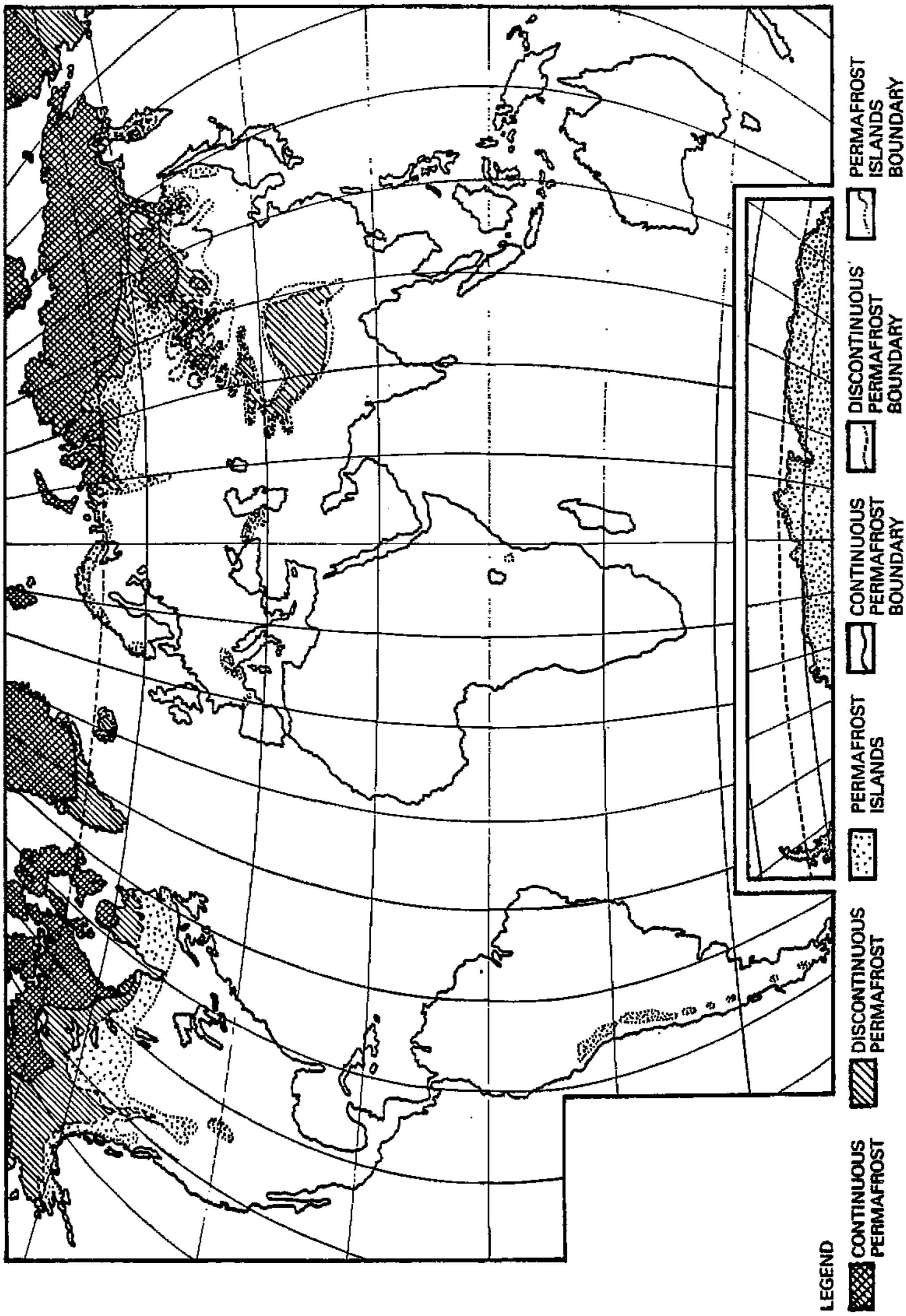


Figure 7.2 Schematic representation of the interrelations in the atmosphere -'buffer layer'- permafrost system (Nieuwenhuijzen and Koster, 1989)

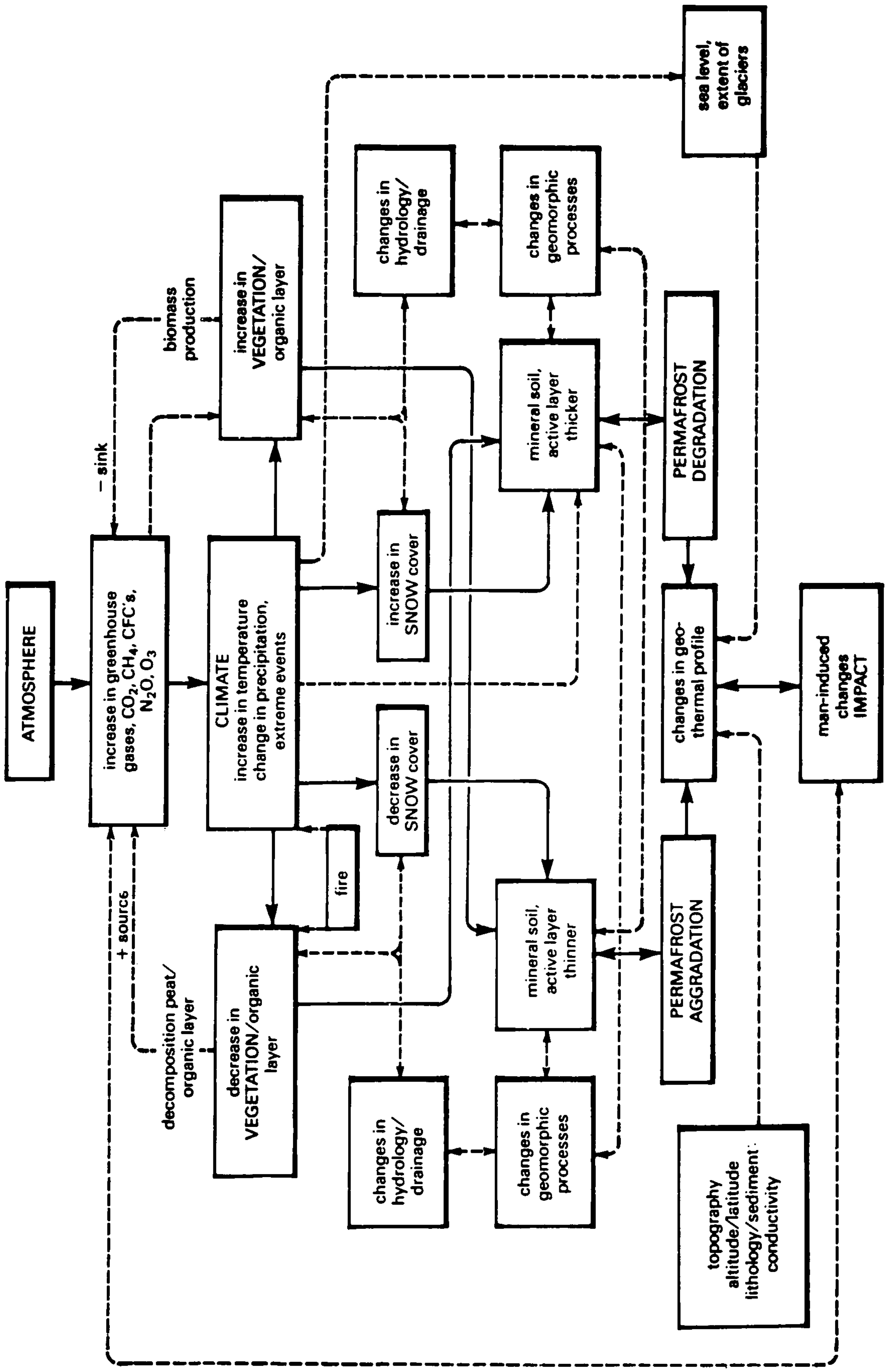


Figure 7.3 **Projected changes in the distribution of continuous permafrost in the USSR as a result of a 2°C increase in mean annual global temperature**

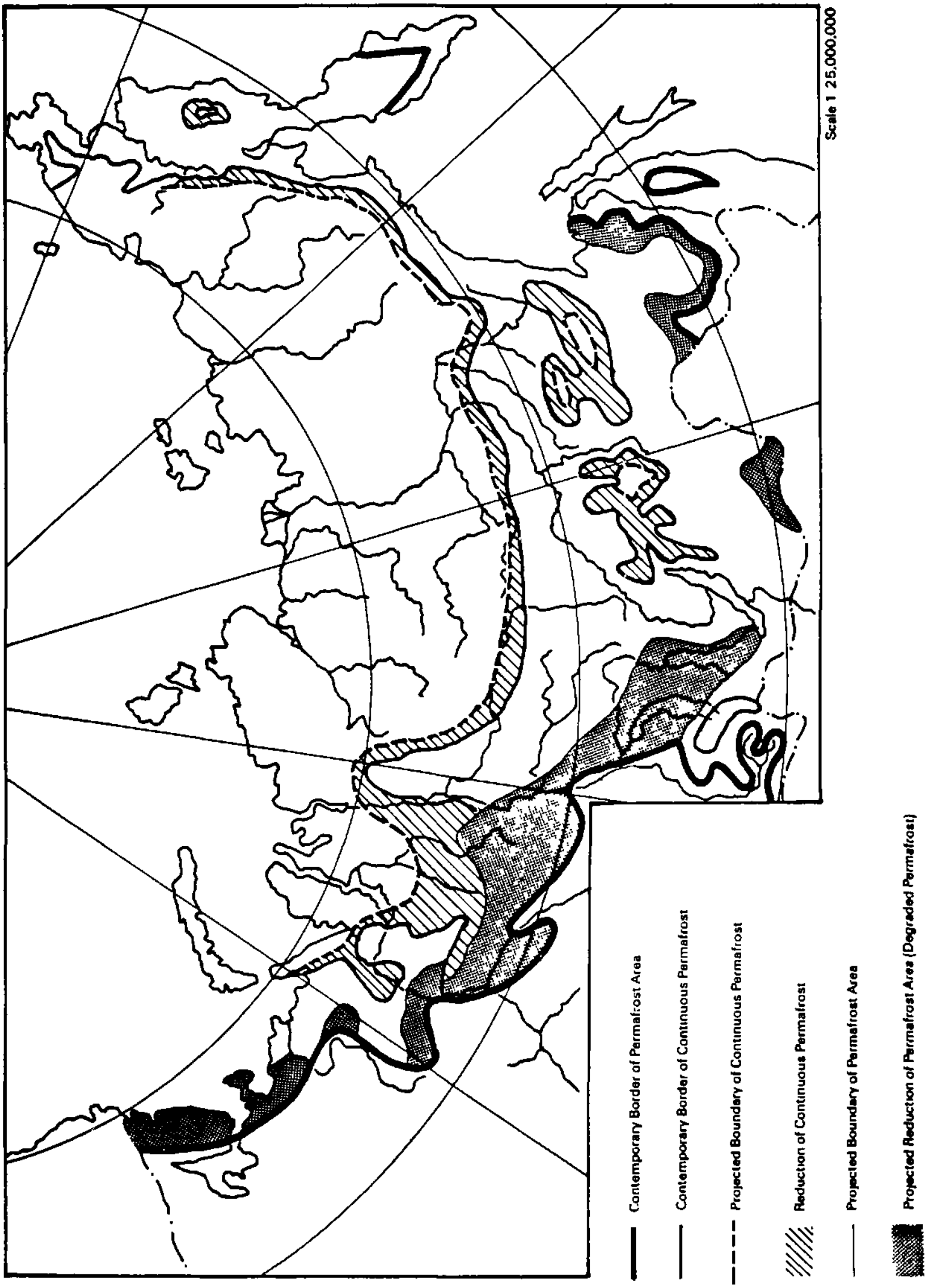


Figure 7.4a Projected changes of permafrost in the USSR along a N-S transect at approximately 83-85° E longitude (Velichko et al., 1990)

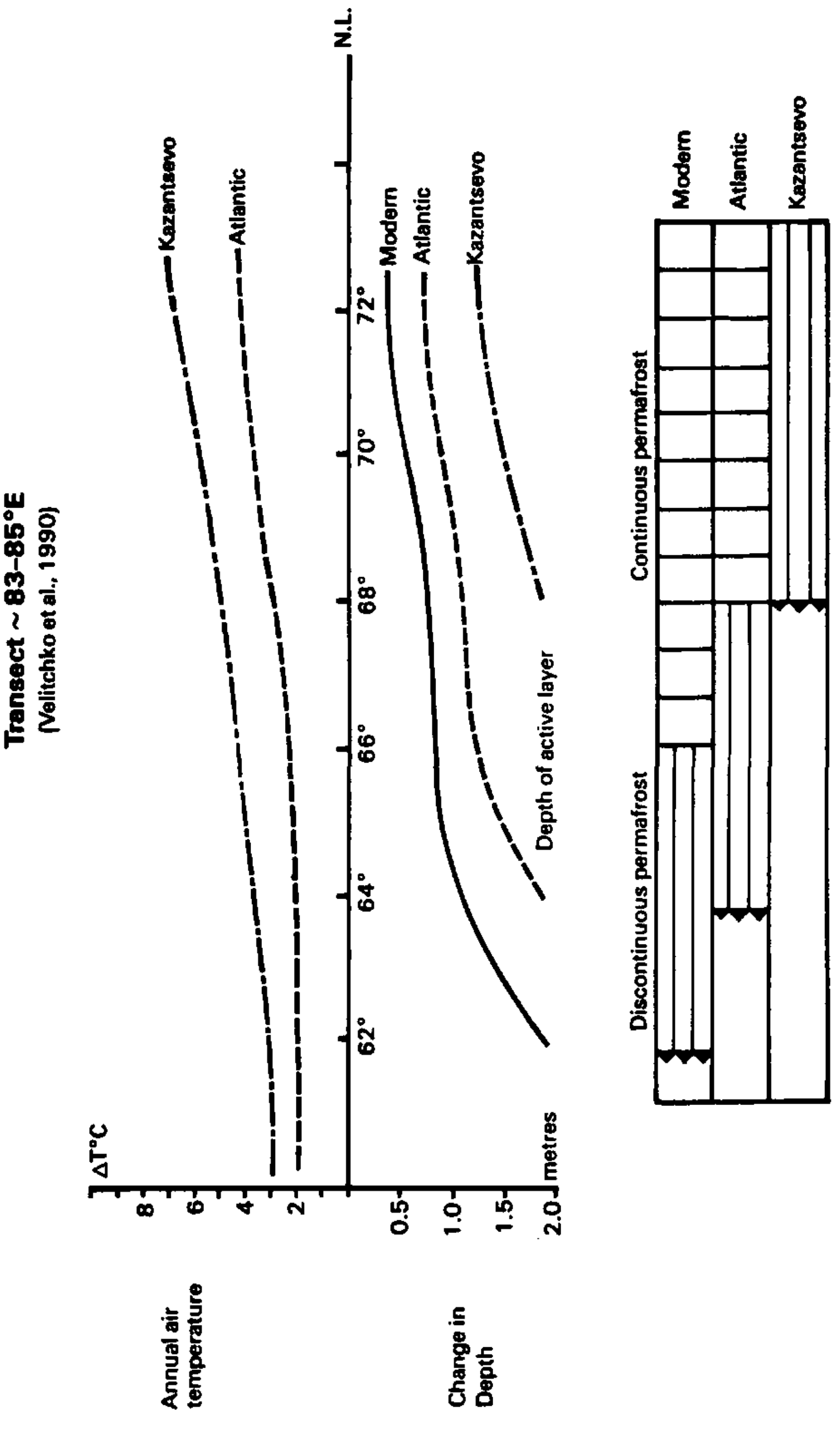
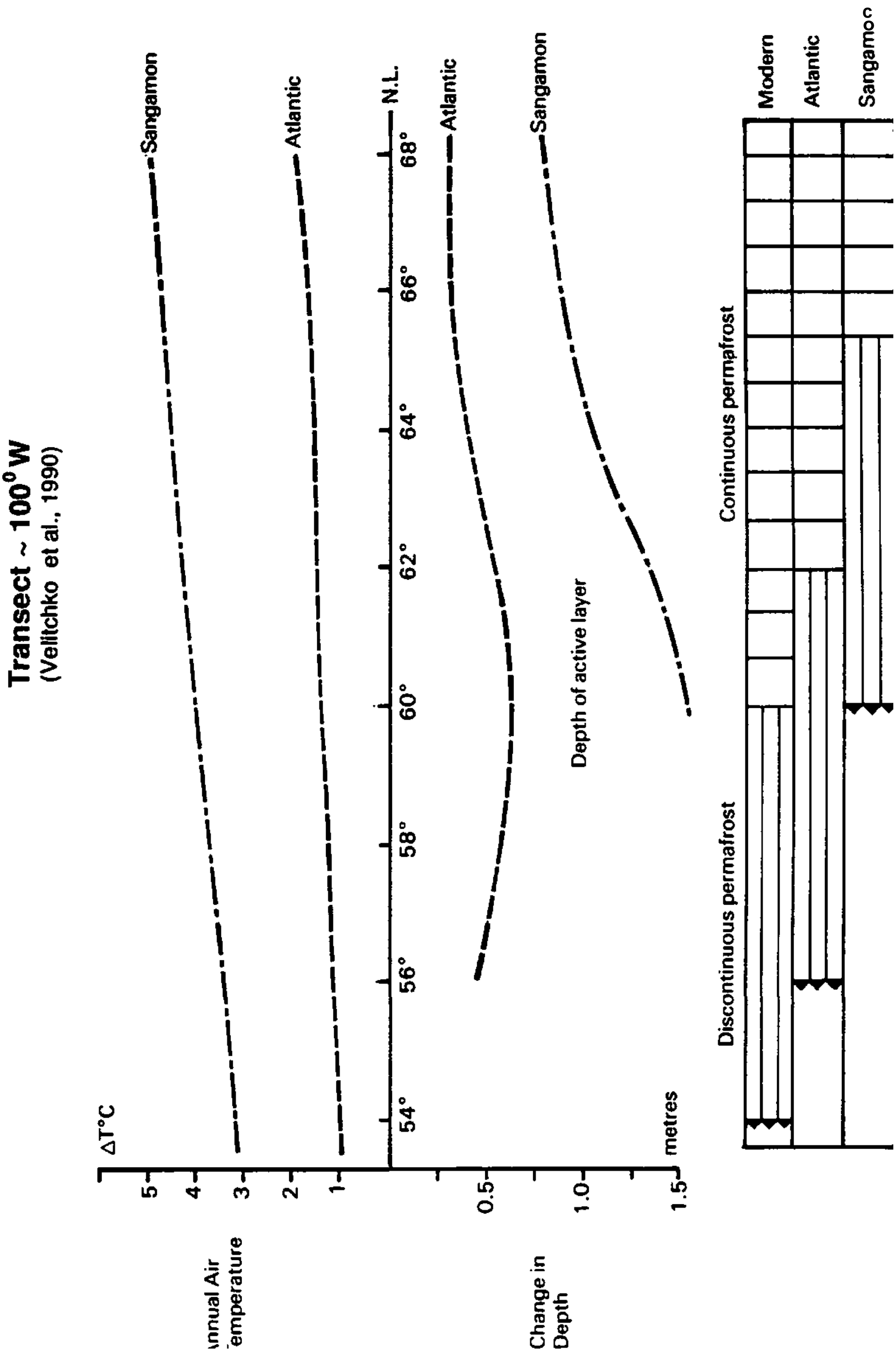


Figure 7.4b Projected changes of permafrost in Canada along a N-S transect at approximately 100° W longitude (Velichko et al., 1990)



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This is the Report of Working Group II of the Intergovernmental Panel on Climate Change, which was set up jointly by the World Meteorological Organization and United Nations Environment Programme in 1988. It is an assessment of the physical and biological impacts of climate change and forms the companion volume to the Report of Working Group I, the IPCC Scientific Assessment.

The topics covered by this assessment include:

- Agriculture and forestry
- Natural terrestrial ecosystems
- Hydrology and water resources
- Human settements and socio-economic activities
- Oceans and coastal zones
- Cryosphere and permafrost

Several hundred international scientists participated in the preparation and review of this assessment, making it the most authoritative statement of the views of the majority of the international scientific community at this time. While the information presented here is the best available, it is clear that there are gaps in our knowledge that require further research.

The assessment will provide informed input to the scientific, political and economic debates and negotiations that will take place in the immediate future. Appropriate strategies in response to the issue of climate change can be based on the scientific foundation that the Report provides. This assessment is, therefore, an essential reference for all who are concerned with climate change and its consequences.

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