# Policymaker Summary of Working Group II (Potential Impacts of Climate Change)

## Executive Summary

1. 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 socio-economic implications of possible climate changes over the next decades caused by increasing concentrations of greenhouse gases.

2. 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.

3. 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.

4. Any predicted effects of climate change must be viewed in the context of our present dynamic and changing world. Large-scale natural events such as El Niño can cause significant impacts on 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.

5. 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.

6. 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, e.g. agriculture, forestry and public health. This is one of the responsibilities of Working Group III.

7. 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

8. 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.

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

### Agriculture and forestry

10. 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.

11. 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.

12. 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 wildfire 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

13. 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.

14. 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.

15. 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.

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

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

18. 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

19. 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.

20. 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 socio-economic 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, energy, transport, and industrial sectors, human health and air quality

21. The most vulnerable human settlements are those especially exposed to natural hazards, e.g. 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.

22. 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 jeopardize 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.

23. 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

24. 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 over-harvesting. A 30—50 cm sea-level rise (projected by 2050) will threaten low islands and coastal zones. A 1 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.

25. 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

26. 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.

27. 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.

28. 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.

29. 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

30. 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.

31. Some of these topics are already being covered by existing and proposed programmes 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.

# 1. Scenarios

1.0.1 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 predicted world population is expected to be above 10 billion by the middle of the next century; this growth will be unevenly distributed on a regional basis and will impact on already vulnerable areas;

- 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.

1.0.2 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.

1.0.3 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°.

1.0.4 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 also 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.

1.0.5 The smaller rise does 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.

1.0.6 The scenarios of Working Group II are derived both from General Circulation Models and from palaeoanalog 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.

1.0.7 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 the table overleaf. 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.

1.0.8 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 2030 have been given for central North America, southern Asia, Sahel, southern Europe and Australia. These are reproduced in the table overleaf and are broadly similar to those used by Working Group II.

1.0.9 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.

## 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 of 1.5°C, these values should be reduced by 30%; with the high estimate of 4.5°C, they should be increased by 50%. Confidence in these regional 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 increases 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, throughout the region, there are areas of both increase and decrease in both parameters throughout the region.

*Southern Europe (35°-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°-115°E)*
The warming ranges from 1 to 2°C 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 sub-continental level.

1.0.10 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.

1.0.11 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.

1.0.12 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.

### *Paleoclimatic analogues used by Soviet scientists*

| **Period** | **Analogue** (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 | 2050 | +4 | 500-600 | 560 |

# SUMMARY OF FINDINGS

## 2 Potential impacts of climate change on agriculture, land use and forestry

### 2.1 Potential impacts on agriculture

*Major findings*

- Sufficient evidence is now available from a variety of different studies to indicate that changes of climate would have an important effect on agriculture, including livestock. Yet the fact that there are major uncertainties regarding likely effects in specific regions should be a cause for concern. 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, diseases, pests and weeds associated with climate change, necessitating innovation in technology and agriculture management practices. There may be severe effects in some regions, particularly in regions of high present-day vulnerability that are least able to adjust technologically to such effects.

- 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 will be largely confined to the Northern Hemisphere.

- On balance, the evidence is 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; but the cost of achieving this is unclear. Nonetheless, climate changes may intensify difficulties in coping with rapid population growth.

***Principal issues***

*Magnitudes of possible dislocation*

2.1.1 Under the estimate of changes in productive potential for the changes of climate outlined in this report, the cost of producing some mid-latitude crops, such as maize and soybean, 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, but these effects may be limited by increased cloudiness and temperature. The average global increase in overall production costs due to climate change could thus be small.

2.1.2 Much depends on the possible benefits of the so-called 'direct' effects of increased $CO_2$ on crop yield. If plant productivity were substantially enhanced and more moisture were available in some major production areas, then world production of staple cereals could increase relative to demand. 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 change could increase significantly.

*Most vulnerable regions and sectors*

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

2.1.4 In addition, certain regions that are currently net exporters of cereals could also be characterized by reduced productive potential as a result of climate changes. Any decrease in production in these regions could markedly affect future global food prices and patterns of trade. These regions might include, for example, Western Europe, southern US, parts of South America, and Western Australia.

*Effect of altered climate extremes*

2.1.5 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 and livestock could increase significantly in some regions as a result of a 1°C to 2°C increase in mean annual temperatures. Similarly, reduction in average levels of soil moisture as a result of higher rates of evapotranspiration could increase substantially the number of days below a minimum threshold of water availability for given crops.

2.1.6 Although at present we know little about how the frequency of extreme events may alter as a result of climate 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, changes in rainfall distribution or increases in evapotranspiration could markedly increase the probability, intensity and duration of drought in currently drought-prone (and often food-deficient) regions. Increase in drought risk represents potentially the most serious impact of climate change on agriculture at both the regional and global level.

### *Effects on crop growth potential, land degradation, pests and diseases*

2.1.7 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 more efficient under higher $CO_2$ levels. However, it is not clear how far the potentially beneficial 'direct' effects of enhanced atmospheric $CO_2$ will be manifested in the farmer's field.

2.1.8 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 realized. Moreover, shifts of moisture limits in some semi-arid and sub-humid regions could lead to significant reductions of potential with serious implications for regional food supplies in some developing countries. Horticultural production in mid-latitude regions may be reduced owing to insufficient accumulated winter chilling. The impact of climate change will be far greater for long-lived horticultural fruit crops, with long establishment periods, than for annual crops where new cultivars can quickly replace others.

2.1.9 Temperature increases may extend the geographic range of some insect pests, diseases and weeds, allowing their expansion to new regions as they warm and become suitable habitats. Changes in temperature and precipitation may also influence soil characteristics.

### *Regional impacts*

2.1.10 Impacts on potential yields are likely to vary greatly according to types of climate change and types of agriculture.

2.1.11 In the northern mid-latitude regions, where summer drying may reduce productive potential (e.g. in the south and central US and in southern Europe), yield potential is estimated to fall by 10—30% under an equilibrium 2 x $CO_2$ climate by the middle of the next century. 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, terrain and land use.

2.1.12 There are indications that warming could lead to an overall reduction of cereal production potential in North America and to 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 and North America, but output in the southern areas of these regions could only increase if corresponding increases in soil moisture were to occur; this is at present uncertain.

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

### *Adaptation in agriculture*

2.1.14 In some parts of the world, climatic limits to agriculture are estimated to shift poleward by 200—300 km per degree of warming. The warming-induced upwards shift in thermal zones above mountain slopes could be in the order of 150—200 m.

2.1.15 Agriculture has an ability to adjust, within given economic and technological constraints, to a limited rate and range of climate change. This capability varies greatly between regions and sectors, but no thorough analysis of adaptive capacity has yet been conducted for the agriculture sector.

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

## ***Recommendations for action***

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

2.1.18 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 generalizing about effects on food production at the regional or world scale. Further research in vulnerable regions in particular should be encouraged.

- Improved understanding of the effects of changes in climate on other physical processes is needed: for example on rates of soil erosion and salinization; 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, 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 (e.g. employment and income, equity considerations, farm infrastructure, and support services).

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

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

## 2.2 Potential impacts on managed forests and the forest sector

2.2.1 All impacts referred to in this section reflect the current uncertainty in the extent of warming, and levels and distribution of precipitation. They reflect the consensus that anthropogenic change is occurring; the direction is towards higher temperatures, with the extent affected by latitude and continentality.

2.2.2 The distinction between managed and unmanaged forests is often unclear, but it is taken here to be one of degree in the intensity of human intervention. In managed forests, harvesting takes place and the forests are renewed, replaced or restructured in such a way that actual physical inputs are needed to achieve goals.

2.2.3 Managed forests are quite distinct from the unmanaged forests. They supply a wide variety of products and are found in a wide variety of countries with different social, physical and political environments. The intensity of forest management may not necessarily parallel the degree of economic development; different countries depend to different degrees on the products from forests. Therefore the severity of the impacts will vary among countries as will the ability to respond. In tropical countries the managed forests characteristically employ exotic species, whereas in the northern countries greater reliance is placed on indigenous species.

### *Biophysical effects on forest ecosystems*

2.2.4 Impacts on forest ecosystems will be at the tree and microsite levels, at the stand/watershed level and at the regional level. Impacts on individual trees include tolerance of drought and winds, the possible effects of altered seasonality (active vs dormant stages), altered photosynthetic rates and increased water use efficiency. At the microsite level, moisture may be limited and biological soil processes may be enhanced. Forest renewal will be adversely affected if there is a shortage of moisture at the critical establishment phase.

2.2.5 On stand levels, insects and diseases can be expected to cause significant losses to forests and these losses can be expected to increase with increasing change. Fire severity will increase, and while managed forests may have less fuel available than unmanaged ecosystems, this will not lessen the incidence of fire, nor will it affect the weather conditions giving rise to the rates of spread or the extent of the areas burned. Developed countries can barely cope with the current state and the extent of areas burned seem to be rising. The incidence of fire may be less in the tropics as the climate there changes less, but many plantations are in semi-arid zones and will suffer adverse impacts. Costs associated with flooding, resulting from rising sea-levels and disruption of weather patterns, can be expected. There will be problems in using the lower quality wood grown under stress and large costs associated with moving processing facilities and infrastructure as the wood supply zones move northward. The most important feature of these costs and disruptions from a global point of view is that the changes will differ among countries and that some countries are better able than others to cope with the impacts.

2.2.6 Major forest-type zones and species ranges could shift significantly as a result of climate change. Results of several Northern Hemisphere studies show that both high-latitude and low-latitude boundaries of temperate and northern forests (and tree species) may shift hundreds of kilometres poleward. In contrast, studies in the Southern Hemisphere suggest that Australian species could adapt and grow at temperatures much warmer than those of their natural distribution.

2.2.7 At the stand level, the following effects of climate change on forests are likely: increased mortality owing to physical stress: increased susceptibility to and infestations of insects and diseases; increased susceptibility to and incidences of fire; changed stand growth rates, both increases and decreases; more difficult stand establishment by both natural and artificial regeneration; and changed composition of species.

2.2.8 Two broad types of forests are likely to be sensitive to a changing climate: (i) boreal forests, where stands are mainly even-aged and often temperature-limited, and where temperature changes are expected to be large; and (ii) forests in arid and semi-arid regions where increased temperatures and stable or decreasing precipitation could render sites inhospitable to the continued existence of current forest stands. However, there could be compensating effects of faster growth owing to higher ambient $CO_2$.

### *Socioeconomic implications*

2.2.9 All countries use forests for heating, cooking and food. The degree to which people are dependent on these, however, varies widely. Forest ecosystem changes and tree distribution have no regard for political or administrative boundaries. Managed forests have, by definition, high levels of investment in them; some countries are better able than others to tolerate the risk to, and possible loss, of these investments.

2.2.10 Intensively managed forests have high inputs from choice of species, sites, spacing, tending, thinning, fertilization and protection. These interventions are costly and some countries may not be able to supply the inputs necessary to establish, maintain and protect the investments.

2.2.11 Increased protection costs will be unevenly borne and could encourage poorer countries to accelerate harvesting, reduce rotation periods and engage in other practices, which may not be sustainable. More data are needed on these secondary and insidious effects of climate change. Associated disruptions in the social fabric of many countries may impact adversely on forests, as instances of arson or other damage do now.

2.2.12 The socioeconomic implications of shifts in the ranges of tree species will be influenced by the fact that climate will probably change much faster than tree species can naturally respond (e.g. through migration).

2.2.13 Moreover, new sites may not be hospitable, having evolved over thousands of years under other climatic and vegetative regimes. The suitability of new ranges and the actual composition and growth patterns of forests under new climates will have no regard for non-ecological boundaries such as watersheds, ownerships, parks, nature reserves and recreation areas.

2.2.14 It is concluded that climate change could more likely exacerbate most current and near-term issues and tensions rather than relieve them. This finding is very dependent on the assumption that during the next 30—50 years, in response to climate change, forests everywhere in the world will be prone to some measure and form of decline. These changes will be taking place at the same time as a substantial increase in population with increased demands. If, on the other hand, forests in some regions are largely unaffected by climate change, or actually experience increased growth rates, then perhaps most of the issues and tensions could be at least partly relieved.

### *Adaptation*

2.2.15 Much can be done to reduce the susceptibility of socioeconomic systems to climate-induced forest declines. Appropriate measures include the whole array of forest-management tools, to be chosen and implemented as local conditions warrant, but some may be detrimental to other indicators, for example, wildlife or recreation.

2.2.16 For wood supply, the forest-products industry can move processing technology towards new kinds and qualities of fibre, and plan new mills in areas improving in wood-supply potential. Governments can support efforts in economic diversification in forest-based communities, and engage in improved long-range planning for future changes in land potential for forestry. The provision of recreational facilities is another example of an important forest-based economic sector. Governments and private firms must anticipate how forested landscapes might change, and plan accordingly to divest themselves of the old facilities and invest in the new.

### ***Recommendations for action***

2.2.17 The ability to deal with climate change and the forest sector is related to the amount of knowledge available. There are uncertainties to be considered: for instance, in the future, will the same tensions and issues have similar high priority? Studies of the socioeconomic impacts must be global in scope, international in organization, institutional in focus and historical in breadth. We need regional climate scenarios and better information on stand-level responses, the biological relationship between species and sites and the inherent variability of species. Changing climates demonstrate the need for strategies in active management in the forest sector. Even better knowledge is needed of the potential role of forest management in mitigating impacts and exploiting opportunities from climate change.

2.2.18 A major impact, of which there is evidence now, will be considerable apprehension on the part of the general public, particularly those dependent on the forest sector for their livelihood. Public cooperation in the implementation of decisions will be required for dealing with a problem which has biological rather than ideological solutions.

2.2.19 Research on the socioeconomic impacts of climate change must focus on the transitional climates occurring over the next several decades, not only at specific points in time. This reflects the way people live—in specific localities and in real time. It makes sense to prepare for serious impacts by implementing policies which are biologically sustainable, even if the eventual changes are minimal.

2.2.20 Examining biogeochemical changes on a global scale is complex enough; adding humans as a variable factor complicates the issue even more. 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, together with the cultural diversity that distinguishes and may dominate our actions.

2.2.21 The nature and temporal/spatial distribution of climate change itself is highly uncertain, as are the various ways by which a changing climate could influence forests and their growing sites, and the various repercussions this might have on our uses of forests. Moreover, the means by which society might cope with the changing environmental and socio-economic conditions, in a context in which those conditions are rapidly changing quite independently of climate change, are largely unexplored so far.

2.2.22 The following major research and assessment initiatives should be developed and pursued in the near future (early 1990s) to begin to shed light on the impacts discussed in this section: (i) more secure regional climate scenarios; (ii) simulation of impacts of climate change on managed forest stands; (iii) modelling studies for better understanding of matches between species and sites; (iv) analyses of the potential role of forest management in mitigating undesirable impacts and capitalizing on desirable impacts of climate change; (v) regional analyses of potential disruption of wildlife habitat and the recreational potential of forests due to forest-structure changes brought on by climate change; (vi) regional analyses of potential socioeconomic repercussions of fluctuations in timber supply due to climate change on rural communities, industrial concerns, markets and trade in forest products, and government;. (vii) synthesis studies of the policy possibilities for the forest sector to prepare for climate change; and (viii) periodical assessment of the destruction of tropical forests using remote sensing.

# 3 Potential impacts of climate change on natural terrestrial ecosystems and the socio-economic consequences

## *Major findings*

3.0.1 Major findings include;

- Global increases in the atmospheric concentration of greenhouse gases and related climatic changes will have significant consequences for natural terrestrial ecosystems and related socioeconomic systems.

- Climatic zones could shift several hundred kilometres towards the poles. Flora and fauna would lag behind these climatic shifts, surviving in their present location; they would therefore find themselves in a different climatic regime.

- The rate of projected climatic 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 these responses may be sudden or gradual.

- New climatic regimes may be less hospitable under some circumstances (e.g. towards lower latitudes and lower altitudes) and may be more hospitable under others (e.g. towards higher latitudes). Vegetation zone changes are projected to be greatest where the land is classified as polar desert, tundra and boreal forest.

- Ecosystems are not expected to move as a single unit, but would have a new structure as a consequence of alterations in species distributions and abundance.

- Some species could be lost owing to increased stresses leading to a reduction in global biological diversity, whereas other species may thrive as stresses decrease.

- Most sensitive are those communities in which the options for adaptability are limited (e.g. montane, alpine, polar, island and coastal communities, remnant vegetation, and heritage sites and reserves) and those communities where climatic change adds to existing stresses.

- Increased incidents of disturbances such as pest outbreaks and fire are likely to occur in some areas and these could enhance projected ecosystem changes.

- The direct effects of increased atmospheric concentrations of $CO_2$ may increase plant growth, water use efficiency and tolerance to salinity, though this positive effect could be reduced over time by ecosystem feedbacks. Enhanced levels of air pollution could also reduce this positive effect.

- 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 affected. Important fibre products, recreation and tourism industries could also be affected in some regions.

## *Principal issues*

3.0.2 The projected changes in climate will present these ecosystems with a climate warmer than that experienced during their recent evolution and there will be warming at a rate 15—40 times faster than past glacial-interglacial transitions. This combination of relatively large and fast changes in climate will cause disruption of ecosystems, allowing some species to expand their ranges while others will become less viable and, in some cases, may disappear.

3.0.3 Current knowledge does not allow a comprehensive and detailed analysis of all aspects of the impacts of climate change on natural terrestrial ecosystems. It is possible, however, to make some plausible implications. All estimates presented below are based on scenarios of enhanced atmospheric concentrations of greenhouse gases and related changes in global climate. It is impossible to evaluate the consequences of change in climatic variability since the required climatic analyses are not available.

### *Particularly sensitive species*

3.0.4 The species which are particularly sensitive to climatic changes are:

- species at the edge of (or beyond) their optimal range;
- geographically localized species (e.g. those found on islands, on mountain peaks, in remnant vegetation patches in rural areas, and in parks and reserves);
- genetically impoverished species;
- specialized organisms with specific niches;
- poor dispersers;
- more slowly reproducing species; and
- localized populations of annual species.

3.0.5 This would suggest that montane and alpine, polar, island and coastal communities, and heritage sites and reserves are particularly at risk, since their component species may not be able to survive or adapt to climate change because of the limited number of adaptive options available to them.

### *Changes in the boundaries of vegetation zones*

3.0.6 Projected changes in global temperature of 1.5°—4.5°C and changes in precipitation will result in the movement of the boundaries of vegetation zones, and will impact on their floristic composition and associated animal species. Boundaries (e.g. boreal-tundra, temperate forests, grasslands etc) are expected to shift several hundreds of kilometres over the next 50 years. Real rates of the movement of species, however, will be restricted by limits on their ability to disperse and the presence of barriers to dispersion: they will, therefore, average approximately 10-100 m/year.

3.0.7 Both coniferous and broad-leaved thermophilic tree species will find favourable environments much further poleward than their current limits. In the northern parts of the Asian USSR, the boundary of the zone will move northward 40°-50° of latitude (500—600 km). The tundra zone is expected to disappear from the north of Eurasia.

3.0.8 Expected changes in precipitation will allow species to extend their boundaries equatorward. As a result, the broad-leaved species range will expand and these ecosystems will be more maritime in terms of species composition. The forest steppe subzone in the European USSR will change while in southern portions of western Siberia the forest-steppe boundary could move up to 200 km.

3.0.9 In the semi-arid, arid and hyper-arid ecoclimatic zones of the Mediterranean, greenhouse-gas-induced climate change will reduce plant productivity and result in desertification of the North African and Near Eastern steppes owing to increased evapotranspiration. 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).

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

### *Changes within ecosystems*

3.0.11 Projected greenhouse-gas-induced climate changes will profoundly affect hydrologic relationships in natural terrestrial ecosystems, both directly by altering inputs of precipitation, runoff, soil moisture, snow cover and melt, and evapotranspiration, as well as indirectly by altering sea and lake levels which influence water levels in coastal and shoreline ecosystems.

3.0.12 The seasonality of rainfall also affects its impact. A lengthening of the dry season or, conversely, an increase in ground-water table levels could both accentuate salinization problems. In Mediterranean and semi-arid climates, where evapotranspiration exceeds precipitation for long periods and increased percolation from vegetation clearing or excessive irrigation may have raised the water table, surface soil salinization can be a major problem. Such salinization can kill all but the most halophytic vegetation, increase soil erosion and reduce water quality. Salinization is already a problem in many Mediterranean and semi-arid regions (e.g. coastal Western Australia, the Mediterranean, subtropical Africa) and is a major cause of increased desertification.

3.0.13 Greenhouse-gas-induced climatic changes will affect the structure and composition of natural terrestrial ecosystems as a result of altered relationships within these ecosystems, perhaps leading to the introduction of new species.

3.0.14 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 as climate change causes increased frequencies of droughts and fires, and invasion of species. One species that might spread, given such conditions, is Melaleuca quinquenervia, a 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.

3.0.15 Pests and pathogens, in some cases, are expected to increase their ranges as a result of climate change and, in the case of insects, their population densities. This could place at risk the health of ecosystems, and thereby play an important role in determining future vegetation and animal distributions

3.0.16 Pest outbreaks can also be expected as a result 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 truncata). 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. With insufficient reserves to replace current tissue. the tree is weakened. and becomes more susceptible to pathogens and insects. Following repeated drought episodes. several (Nothofagus) species succumbed to defoliation insects. This would be exacerbated by non-induced climate change.

3.0.17 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, an increase in average temperature and any change in the distribution of seasonal wetlands will alter the temporal and spatial distribution of these diseases.

3.0.18 Higher temperatures and changed precipitation may well lead to increased drought frequency and fire risk in many forested areas. Coupled with probably increased fuel density because of the direct effects of increased ambient $CO_2$ on forest understorey, this could lead to increased exposure of forests to fire, which would tend to accelerate changes in ecosystem composition under conditions of changing climate.

3.0.19 In areas with a distinct wet and dry season (parts of the tropic, and all of the Mediterranean-climate regions), change 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 could increase fuel loadings in most of the subtropical and temperate woodlands of Mexico, which would suggest increased fire frequencies.

3.0.20 Global biological diversity is expected to decrease with possible socioeconomic consequences as a result of climate change; however, some local increases may also result, especially over the longer term. The resulting impacts on biological diversity are dependent on the balance between changes in species interactions and adaptation through migration.

3.0.21 Warming could set off a chain of extinctions by eliminating keystone herbivores or their functional counterparts in other ecosystems. For example, 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.

3.0.22 The direct effects of increased atmospheric concentrations of $CO_2$ may increase the rate of plant growth; however, man-induced changes in the chemical composition of the atmosphere (e.g. ozone) and ecosystem feedbacks could reduce this positive effect over time.

## *Recommendations for action*

3.0.23 While the specific impacts of global warming on any one region or a single species are to some degree matters of conjecture, there are some clear conclusions that can be made. Natural terrestrial ecosystems will change in make-up and shift in location, and those species which can adapt and shift will survive. The sensitive species, especially those for which options are limited, will dwindle and disappear.

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

3.0.25 These limitations can be addressed by:

- assembling relevant inventories of species and ecosystems;
- initiating and maintaining integrated monitoring programs;
- gathering information on relative species and ecosystems sensitivities to climate change;
- initiating and supporting regional, national and international research and impacts programs; and
- educating resource managers and the public about the potential consequences of climatic change for natural terrestrial ecosystems.

# 4 Potential impacts of climate change on hydrology and water resources

## *Major findings*

4.0.1 Major findings include:

- For many watersheds worldwide, especially those in arid and semi-arid regions, runoff is very sensitive to small changes and variations in climate. For example, a 1°C to 2°C temperature increase coupled with a 10% reduction in precipitation could conceivably produce a 40—70% reduction in annual runoff.

- Based on empirical data and hydrological models, annual runoff appears to be more sensitive to changes in precipitation than to changes in temperature. However, in regions where seasonal snowfall and snowmelt are a major part of the total water supply, the monthly distribution of runoff and soil moisture is more sensitive to temperature than to precipitation.

- The construction of hypothetical scenarios provides a range of runoff responses and the characteristics of those responses for particular areas. However, credible forecasts for any specific region, sufficient to designate either direction or magnitude of change, are not yet available. We can conduct warm sensitivity analysis using General Circulation Models while the scientific basis slowly improves.

- Vulnerabilities in present water uses (ie where demand exceeds firm yield) and conflicts among current uses are likely to be exacerbated by global warming in most arid and semi-arid regions.

- The regions that appear to be at greatest risk, in terms of serious threats to sustaining the population are: Africa—Maghreb, Sahel, the north of Africa, southern Africa; Asia—western Arabia, Southeast Asia, the Indian subcontinent; North America—Mexico, Central America, southwest US; South America—parts of eastern Brazil; Europe—Mediterranean zone.

- The relative degree of water management (storage versus mean annual flow) is a primary determinant in adapting to changes in the mean annual variability.

- It is essential that future design of water resource engineering takes into account that climate is a non-stationary process, and that structures with a design life of 50 to more than 100 years should be designed to accommodate climatic and hydrometeorological conditions which may exist over the entire life of the structure.

## *Principal issues*

4.0.2 If worthwhile 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.

4.0.3 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.

4.0.4 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 about the various methods for estimating future change must be made available to the management community.

## *Regional impacts*

### Continental/national

4.0.5 Based on palaeoclimatic analogs coupled with physically based water-balance models, annual runoff over the whole of the USSR is projected to rise, although runoff is expected to decrease slightly in the forest steppe and southern forest zones. In any case, winter runoff is expected to increase in the regions with snowfall and snowmelt. Serious flooding problems could arise in many northern rivers of the USSR.

4.0.6 An assessment of all the river basins in the US shows that the arid and semi-arid regions of the US would be most severely affected by global warming, even though there is a high degree of water control. The competing uses of agricultural irrigation, municipal water supply, and generation of hydroelectric power, have stressed even the present system. All other regions in the US will probably suffer adverse water-resource impacts to some degree, whether for generation of hydroelectric power, municipal water supply shortages, or agricultural irrigation.

4.0.7 An assessment of the general circulation model studies for the nations of the European Economic Community (EEC) indicates that precipitation and runoff may increase in the northern nations, possibly causing flooding problems in low-lying countries. The Mediterranean countries of the EEC may experience a decline in runoff, thereby increasing the already serious and frequent water supply shortages occurring in that region. It is most probable that agriculture will suffer the most adverse effects.

4.0.8 In Japan, prolonged periods of droughts and shorter periods of intense precipitation may be likely. Current storage capacity is limited and a large proportion of the population is located on flood-plains. Water demand can be expected to increase, which will seriously stress the existing water management system.

4.0.9 An increase in precipitation and consequent flooding, along with overloads of stormwater/sewerage systems leading to degradation of surface water quality, is possible in New Zealand.

4.0.10 The UK can expect an increase in mean annual runoff over most of the country, but with a stronger seasonal variation in peak flows, imposing the need for redesigning existing water management systems.

**River basins and critical environments**

4.0.11 Runoff in the Volga River basin, after undergoing an initial decrease through the year 2000, is expected to increase after that year.

4.0.12 Studies indicate that hydrological conditions in the Sahelian zone are very sensitive to climatic conditions, especially precipitation. Research suggests, for example, that a 20% to 30% decrease in precipitation could lead to a 15% to 59% reduction in runoff. As for potential changes in water resources in the future, it can be said that the situation is very uncertain. Therefore, additional comprehensive studies of this problem, which is very important for the region, are required.

4.0.13 A study of the Sacramento-San Joaquin River basin showed how a highly managed water resource system, dependent on snowmelt-generated runoff, would be affected by global warming. Air temperature increases changed the timing and increased the magnitude of snowmelt-generated runoff by 16% to 81%, severely stressing the flood-control capabilities of existing reservoirs. However, summer runoff decreases of 30% to 68%, coupled with soil moisture decreases of 14% to 36% and a doubling of water demand by the year 2020, suggest that serious water use conflicts and periodic shortages are a distinct possibility for this system.

4.0.14 In the Murray-Darling basin of Australia, the use of spatial analogs indicates that precipitation could decrease by 40% to 50%. However, based on general circulation model outputs, the summer-dominant rainfall area of Australia will possibly expand to encompass 75% of the continent by 2035. Runoff could double on the Darling River.

4.0.15 A water supply-demand stochastically-based sensitivity analysis was conducted for the Delaware River basin, a highly urbanized watershed in the northeastern US. Basin-wide estimates of annual runoff indicate a possible decrease of 9% to 25%. Also, the probability of drought increases substantially throughout the basin. The Delaware River supplies a large percentage of New York City's water supply, which is already operating below its safe yield. Reduced flows in the Delaware River would threaten the city of Philadelphia's water supply intakes in the estuarine portion of the river through upstream movement of the freshwater-saltwater interface.

**Large lakes/seas**

4.0.16 The Caspian Sea is the largest closed water body in the world. It receives nearly 80% of its runoff from the Volga River and will respond to the initial decrease in projected Volga River flows to the year 2000, but will increase thereafter. This will greatly improve the severely degraded water quality and ecological conditions in the Sea.

4.0.17 Based on general circulation model results, the Great Lakes are expected to incur net basin runoff decreases of 23% to 51% under an effective doubling of $CO_2$ scenario. Generation of hydro-electric power, the very important commercial navigational uses, and lake water quality which is due to thermal stratification, are expected to be adversely affected.

4.0.18 The Aral Sea would continue to experience water-quality degradation by polluted irrigation return flows, as the precipitation-runoff increases projected for the area would not be enough to compensate for increased expansion of irrigated agriculture.

## *Recommendations for action*

4.0.19 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 development of methods for translating climate model information into a form that provides meaningful input data to watershed and water resource system models.

4.0.20 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.

4.0.21 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.

4.0.22 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.

4.0.23 Very little is currently known about the effects of climate change on water quality. Although concerns about water quality 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.

# 5. Potential impacts of climate change on human settlement, the energy, transport and industrial sectors, human health and air quality

## *Major findings*

5.0.1 Major findings include:

- Throughout the world the most vulnerable populations are farmers engaged in subsistence agriculture, residents of coastal lowlands and islands, populations in semi-arid grasslands and the urban poor in slums in shanty towns, especially in megacities—those with several millions of inhabitants.

- Climate change and even a modest global sea-level rise can be expected to prove disruptive to human settlement in many vulnerable coastal areas of some island nations and communities where drought, floods and changed agricultural growing conditions have affected water resources, energy, public health and sanitation, and industrial or agricultural production.

- Global warming can be expected to cause a significant shift in the permafrost zone; such rapid change will prove quite disruptive to roads, railways, buildings, oil and gas pipelines, mining facilities and infrastructure in the permafrost region.

- Global warming can be expected to affect the availability of water resources and biomass, both major energy sources in a large number of developing countries. Such changes in areas which lose water may jeopardize energy supply and materials essential for human habitation and energy. Climate change will also affects the regional distribution of other renewable energy resources such as wind and solar power.

- Vector-borne and viral diseases such as malaria, schistosomiasis and dengue can be expected under warmer climatic conditions to shift to higher latitudes.

- Should severe weather, such as tropical cyclones, occur more frequently or become more intense as a result of climate changes, human settlement and industry may be seriously affected, with large loss of human life.

## *Principal issues*

5.0.2 The impact on developing countries, many of which lack resources for adaptation, may be particularly disruptive. Understanding likely impacts of climate change on human settlement, energy, transport, industry and human health in such countries should be a high priority, together with reinforcing indigenous capability to design and implement strategies to reduce adverse impacts of climate change.

5.0.3 The impacts of climate change on human settlement and related socioeconomic activity, including the energy, transport and industry sectors, will differ regionally, depending on regional distribution of changes in temperature, precipitation, soil moisture, patterns of severe storm, and other possible manifestations of climate change. As the general circulation model scenarios provided by Working Group I have indicated, changes in some of these climatic characteristics may differ considerably among regions. In addition, the vulnerability to change in climate of human settlement and related economic activity varies considerably among regions and within regions. For example, coastal areas may generally be more vulnerable to climate change than inland areas within the same region.

5.0.4 Development of effective strategies to respond to climate change will require much better capability to predict and detect regional climate change and occurrence of severe meteorological phenomena. A major issue is that of timing. For example, a sea-level rise of 0.5 m over 50 years would have substantially different impacts than the same rise over 100 years. Not only are present-value costs for adaptation measures vastly different, but also much of the present-day infrastructure would have undergone replacement in the longer time period.

## *Human settlement*

5.0.5 A principal difficulty in determining the impact of climate change on human habitat is the fact that many other factors, largely independent of climate change, are also important. One can reliably predict that certain developing countries will be extremely vulnerable to climate changes because they are already at the limits of their capacity to cope with climatic events. These include populations in low-lying coastal regions and islands, subsistence farmers, populations in semi-arid grasslands, and the urban poor.

5.0.6 The largest impacts on humanity of climate change may be on human settlement, with the existence of entire countries such as the Maldives, Tuvalu, and Kiribati imperilled by a rise of only a few metres in sea-levels and populous river delta and coastal areas of such countries as

Egypt, Bangladesh, India, China and Indonesia, threatened by inundation from even a moderate global sea-level rise. Coastal areas of such industrialized nations as the United States and Japan will also be threatened, although these nations are expected to have the requisite resources to cope with this challenge. The Netherlands has demonstrated how a small country can effectively marshal resources to deal with such a threat.

5.0.7 Besides flooding of coastal areas, human settlement may be jeopardized by drought, which could impair food supplies and the availability of water resources. Water shortages caused by irregular rainfall may especially affect developing countries, as seen in the case of the Zambezi river basin. Biomass is the principal source of energy for most of the countries of sub-Saharan Africa, and changed moisture conditions in some areas, reducing this biomass, could pose grave problems for domestic energy production and construction of shelter.

5.0.8 Although there has been only a handful of city-specific studies, they suggest that climate change could prove costly to major urban areas in developed nations. A study has projected that an effective $CO_2$ doubling could produce a major water shortfall for New York City equal to 28% to 42% of the planned supply in the Hudson River Basin, requiring a $3 billion project to skim Hudson River flood waters into additional reservoirs.

5.0.9 Although in the permafrost region global warming may result in expansion of human settlement poleward, thawing of the permafrost may also disrupt infrastructure and transport and adversely affect stability of existing buildings and conditions for future construction.

5.0.10 The gravest effects of climate change may be those on human migration as millions are displaced by shoreline erosion, coastal flooding and severe drought. Many areas to which they flee are likely to have insufficient health and other support services to accommodate the new arrivals. Epidemics may sweep through refugee camps and settlements, spilling over into surrounding communities. In addition, resettlement often causes psychological and social strains, and this may affect the health and welfare of displaced populations.

## *Energy*

5.0.11 Among the largest potential impacts of climate change on the developing world are the threats in many areas to biomass, a principal source of energy in most sub-Saharan African nations and many other developing countries. More than 90% of the energy in some African countries depends on biomass energy (fuelwood). Owing to uncertainties in water resource projections derived from current climate models, it is very difficult to provide reliable regional projections of future moisture conditions in these countries. Drier conditions could be expected in some countries or regions, and in those situations energy resources could be severely impaired. There could be possible compensating effects of faster growth of fuelwood due to higher ambient $CO_2$. Analysis of this situation should be a top priority for energy planners.

5.0.12 In addition to affecting the regional distribution of water and biomass, climate-related changes in cloud cover, precipitation and wind circulation intensity will affect the distribution of other forms of potential renewable energy such as solar and wind power. Understanding these impacts on hydro, biomass, solar and wind energy is particularly important because renewable energy sources are playing a significant role in the energy planning of many countries. This could become an increasingly important concern in developing countries, many of which are facing serious economic pressures from the need to import conventional energy resources.

5.0.13 Developing countries, including many in Africa, depend significantly on hydroelectric power. By changing water resource availability, climate change may make some present hydroelectric power facilities obsolete and future energy planning more troubled, although others may benefit from increased runoff.

5.0.14 Major studies to date of the likely impact of global warming on the energy sector in developed countries are confined largely to six countries: Canada, the Federal Republic of Germany, Japan, the UK, the USSR and the US. Generally, they show differing overall aggregate impacts, depending on how much energy use is related to residential and office heating and cooling. Climate warming will increase energy consumption for air-conditioning and, conversely, lower it for heating.

5.0.15 In addition, the energy sector may be affected by response strategies against global warming, such as a policy on emission stabilization. This may be among the most significant energy sector impacts in many developed countries, enhancing opportunities for technologies that produce low quantities of greenhouse gases. Controversy on the way to obtain $CO_2$-free energy has already risen, particularly the options of increased reliance on nuclear power or hydro-electric power, weighed against related safety and environmental concerns. Energy sector changes in both developing and developed countries may have broad economic impacts affecting regional employment, migration and patterns of living.

## *Transport*

5.0.16 Generally, the impacts of climate change on the transport sector appear likely to be quite modest, with two exceptions. Ultimately, the greatest impact of climate change on the transport sector in developed countries would appear to be changes produced by regulatory policies or consumer shifts designed to reduce transport-related emissions of greenhouse gases. Because of the importance of the transport sector as a source of greenhouse gases, it is already being targeted as a major source of potential reductions in greenhouse gas emissions, with potentially added constraints on private automobile traffic, automotive fuel and emissions, and increased use of efficient public transport.

5.0.17 A second large impact on the transport sector concerns inland shipping, where changes in water levels of lakes and rivers may seriously affect navigation and the costs of barge and other transport. Studies to date, focused entirely on the Great Lakes region of Canada and the US, have shown quite large potential impacts. Climate scenarios have shown a likely drop of lake levels of as much as 2.5 m resulting from an effective $CO_2$ doubling. Such changes could increase shipping costs, but the shipping season could be longer than at present due to decreased ice. Lake and river levels may rise in some other regions with potentially enhanced opportunities for shipping.

5.0.18 Generally, impacts on roads appear likely to be quite modest, except in coastal areas where highways or bridges may be endangered by sea-level rise or in mountainous regions where potentially increased intensity in rainfall might pose the risk of mudslides. Studies in Atlantic Canada and Greater Miami, US, indicate that highway infrastructure costs could prove very costly in such exposed coastal areas. Reduced snow and ice and lessened threat of frost heaves should generally produce highway maintenance savings as suggested by a study of Cleveland, Ohio, US.

5.0.19 Impacts on railways appear likely to be modest, although heat stress on tracks could increase summertime safety concerns on some railways and reduce operational capability during unusually hot periods. Dislocations due to flooding may increase.

5.0.20 There has been little analysis of likely impacts on ocean transport. The greatest effect would appear likely to be some jeopardy to shipping infrastructure such as ports and docking facilities, threatened both by sea-level rise and storm surge. Some climate projections indicate the possibility that tropical cyclone intensity may increase. This could have adverse implications for ocean shipping and infrastructure. On the other hand, decreased sea ice could provide greater access to northern ports and even enable regular use of the Arctic Ocean for shipping. Moderate sea-level rise could also increase the allowable draught for ships using shallow channels.

5.0.21 There is a strong need for analysis of likely impacts of climate change for the transport sector in developing countries, as efficiency of the transport sector is likely to be an essential element in the ability of countries to respond to climate change.

### *Industry*

5.0.22 Studies of likely impacts of climate change on the industrial sector tend to be concentrated heavily on certain sectors such as recreation and only on a handful of developed countries, principally Australia, Canada, Japan, the UK and the US. There is very little analysis of the likely impacts of climate change on industry in developing countries, although there is some evidence to suggest that industry of developing countries may be particularly vulnerable to climate change. An especially important factor is the likely change in the production map of primary products as a result of climate change.

5.0.23 Changes in the regional and global availability and cost of food and fibre may significantly affect the competitiveness and viability of such derivative industries as food processing, forest and paper products, textiles and clothing. Climate change may be expected to have impacts on the availability and cost of food, fibre, water and energy which would differ markedly from region to region.

5.0.24 Just as the motor vehicle and the energy sectors are likely to be influenced by regulatory decisions and shifts in consumer patterns emanating from concerns about limiting greenhouse gas emissions, heavy manufacturing may face readjustment to new situations such as transboundary siting constraints and international mechanisms for development and transfer of new technology. Efficiency in the use of energy may become an even more significant competitive factor in steel, aluminium and other metal industries, and automotive manufacturing. Public concerns about limiting greenhouse gas emissions may also create opportunities for energy conservation or for industries based on 'clean technology'. Studies of likely impacts of climate change on industry tend to be clustered in the recreational sector, where direct impacts of climate change are more ascertainable.

5.0.25 With sufficient lead time, industry may be able to adjust to many of the changes accompanying global warming. Shortages of capital in developing countries which may be vulnerable to flood, drought or coastal inundation may, however, constrain such industry's ability to design effective response strategies.

### *Human health*

5.0.26 Humans have a great capacity to adapt to climatic conditions. However, adaptations have occurred over many thousands of years. The rate of projected climatic changes suggest that the cost of future adaptation may be significant.

5.0.27 A greater number of heatwaves could increase the risk of excess mortality. Increased heat stress in summer is likely to increase heat-related deaths and illnesses. Generally, the increase in heat-related deaths would be likely to exceed the number of deaths avoided by reduced severe cold in winter. Global warming and stratospheric ozone depletion appear likely to worsen air pollution conditions, especially in many heavily populated and polluted urban areas. Climate change-induced alterations in photochemical reaction rates among chemical pollutants in the atmosphere may increase oxidant levels, adversely affecting human health.

5.0.28 There is a risk that increased ultraviolet-B radiation resulting from depletion of the stratospheric ozone layer could raise the incidence of skin cancer, cataracts and snow blindness. The increased skin cancer risks are expected to rise most among fair-skinned Caucasians in high-latitude zones.

5.0.29 Another major effect of global warming may be the movement poleward in both hemispheres of vector-borne diseases carried by mosquitoes and other parasites. Parasitic and viral diseases have the potential for increase and reintroduction in many countries.

5.0.30 Changes in water quality and availability may also affect human health. Drought-induced famine and malnutrition have enormous consequences for human health and survival.

5.0.31 The potential scarcity in some regions of biomass used for cooking, and the growing difficulty in securing safe drinking water because of drought, may increase malnutrition in some developing countries.

### *Air pollution*

5.0.32 SOx, NOx and auto-exhaust controls are already being implemented to improve air quality in urban areas in some developed countries. Concerns about possible energy penalties and overall implications of such control measures for greenhouse gas emissions will need to be incorporated in future planning. Moreover, global warming and stratospheric ozone depletion appear likely to aggravate tropospheric ozone problems in polluted urban areas. The tropospheric temperature rise induced by the enhanced greenhouse effect could change homogeneous and heterogeneous reaction rates, solubility to cloud water, emission from marine, soil and vegetative surfaces, and deposition to plant surfaces of various atmospheric gases, including water vapour and methane. A change in water vapour concentration will lead to changes in the concentration of HOx radicals and $H_2O_2$, which are important for the oxidation of $SO_2$ and NOx in the atmosphere 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 patterns and transformation rates in regional or local sectors. A change in aerosol formation by atmospheric conversion from NOx, and $SO_2$ and windblown dust from arid land could lead to changes in visibility and albedo. Material damage caused by acidic and other types of air pollutants may be aggravated by higher levels of humidity.

### *Ultraviolet-B radiation*

5.0.33 Besides the human health implications of increased ultraviolet-B radiation already discussed, such radiation may also significantly affect terrestrial vegetation, marine organisms, air quality and materials. Increased ultraviolet-B radiation may adversely affect crop yields. There are some indications that increased solar ultraviolet-B radiation which penetrates into the ocean surface zone where some marine organisms live, may adversely affect marine phytoplankton, potentially reducing marine productivity and affecting the global food supply. Increased ultraviolet-B radiation can also be expected to accelerate degradation of plastic and other coating used outdoors. The enhanced greenhouse effect is expected to decrease stratospheric temperatures and this may affect the state of the stratospheric ozone layer.

### ***Recommendations for action***

- Assessment of the vulnerability of countries, especially in the developing world, to gain or loss of energy resources such as hydroelectric power, biomass, wind and solar, and an examination of available substitutes under new climate conditions, should be a high priority.

- Research is critically needed into the adaptability of vulnerable human populations, especially the elderly and the sick, to the occurrence of increased heat stress as well as the potential for vector-borne and viral diseases to shift geographically.

- Policy makers should give priority to the identification of population and agricultural and industrial production at risk in coastal areas subject to inundation from sea-level rise of various magnitudes and to storm surge.

- It is important that developing countries have the capability to assess climate change impacts and to integrate this information into their planning. The world community should assist countries in conducting such assessments and work to create indigenous climate-change impact assessment capabilities in such countries.

## 6. Potential impacts of climate change on the world ocean and coastal zones

### ***Major findings***

6.0.1 The projected global warming will cause sea-level rise, modify ocean circulation, and cause fundamental changes to marine ecosystems, with considerable socioeconomic consequences.

6.0.2 Sea level is already rising on average over 6 cm per 50 years, with important regional variations because of local geological movements. The Greenland and perhaps the Antarctic ice sheets may still be responding to changes since the last glaciation. Fisheries and various coastal resources are presently under growing stress from pollution, exploitation and development, creating serious problems for populations dependent on them. Impacts from the enhanced greenhouse effect, which have been considered by the IPCC, will be added to these present trends.

6.0.3 A 20—30 cm sea-level rise (projected by the year 2050) poses problems for the low-lying island countries and coastal zones, destroying productive land and the freshwater lens. Protecting these areas entails considerable cost.

6.0.4 A 1 m sea-level rise (the maximum projected by the year 2100) would eliminate several sovereign states, displace populations, destroy low-lying urban infrastructure, inundate productive lands, contaminate freshwater supplies and alter coastlines. These effects could not be prevented except at enormous cost. The severity would vary among coastal regions and would depend on the actual rate of rise.

6.0.5 Coastal ecology is affected by the rate of sea-level rise. Too rapid a rise could reduce or eliminate many coastal ecosystems, drown coral reefs, reduce biological diversity and disrupt the life cycles of many economically and culturally important species.

6.0.6 Erosion of wetlands and increasing availability of organic matter from sea-level rise can increase estuarine and near-shore productivity for some decades.

6.0.7 Global warming will change the thermal budget of the World Ocean and shift the global ocean circulation. Changes in ocean circulation, including high-latitude deep water formation, will affect the capacity of the ocean as a sink of atmospheric heat and $CO_2$. Upwellings of nutrient-rich waters associated with major fisheries are also expected to change, causing a decrease in primary production in open ocean upwelling zones and an increase in primary production in coastal upwelling zones. The expected impacts will include chemical changes in biogeochemical cycles such as the global carbon cycle which affects the rate of accumulation of atmospheric $CO_2$.

6.0.8 Adverse ecological and biological consequences will vary by geographic zones of the world's oceans. The loss of habitat will cause changes in biological diversity, redistribution of marine organisms and a shift in the ocean production zones.

6.0.9 A simultaneous rise in both water temperature and sea-level may lead to the redistribution of commercially important species and benthic organisms. Changes in fisheries production may well balance globally in the long term, but there could be important regional shifts in areas of fisheries, with major socioeconomic impacts.

6.0.10 Shipping and ocean transportation will benefit from less sea ice and small increases in depth in harbours, but some ice-dependent marine mammals and birds will lose migratory and hunting routes and essential habitats.

6.0.11 Increase in ultraviolet-B radiation can have widespread effects on biological and chemical processes, on life in the upper layer of the open ocean, on corals, and on wetlands. These impacts are of concern but not well understood.

### *Impacts of sea-level rise on coastal zones*

6.0.12 The magnitude and rate of sea-level rise will determine the ability of social and natural ecosystems to adapt to the rise. Direct effects of the rise are straightforward: inundation of low-lying coastal areas; erosion and recession of sandy shorelines and wetlands; increased tidal range and estuarine salt-front intrusion; increases in sedimentation in the zone of tidal excursion; and increase in the potential for salt water contamination of coastal freshwater acquifers. The predicted changes in climate may also affect the frequency and intensity of coastal storms and hurricanes, which are the major determinants of coastal geomorphic features and extreme high sea-level events.

6.0.13 The socioeconomic impacts of these direct physical effects are uncertain and more difficult to assess, and are region- and site-specific. There are three general impact categories that encompass the physical effects:

- threatened populations in low-lying areas and island nations;
- alteration and degradation of the biophysical properties of beaches, estuaries and wetland;.
- inundation, erosion and recession of barrier beaches and shorelin;.

### *Threatened populations in low-lying areas and island nations*

6.0.14 The most important socioeconomic impact of sea-level rise is the inundation of intensely utilized and densely populated coastal plains. A 1 m rise would produce a coastline recession of several kilometres in a number of countries. Other countries have a substantial proportion of land area between 1 m and 5 m above sea-level, with high density coastal populations. For example, a 1 m sea-level rise could inundate 12—15% of Egypt's arable land and 14% of Bangladesh's net cropped area, displacing millions of inhabitants.

6.0.15 Sea-level rise would also expose a greater proportion of low-lying areas to coastal storm flooding from storm surges. Densely populated urban areas could be protected at great cost, but less densely populated areas stretched out along the coastline could not be protected. In these situations, large-scale resettlement might be necessary. Another consequence of sea-level rise is greater incursion of salt water into freshwater estuarine areas, along with larger tidal excursion. This would reduce the freshwater portion of estuarine rivers, especially during drought periods, adversely affecting municipal and industrial freshwater supplies, and could contaminate coastal groundwater acquifers, which also supply water for municipal purposes in many areas. Many estuarine areas across the world, with large population centres, would be affected, particularly those where a decrease in net freshwater runoff is also projected as a consequence of global warming.

6.0.16 Finally, as sea-level rises, much of the infrastructure in low-lying urban areas would be affected, requiring major engineering design adjustments and investments. In particular, stormwater drainage and sewerage systems of many cities will be affected. Coastal protection structures, highways, power plants and bridges may require redesign and reinforcement to withstand increased flooding, erosion, storm surges, wave attack and sea-water intrusion.

### *Alteration of the biophysical properties of estuaries and wetlands*

6.0.17 An accelerated rise in sea-level could severely redistribute coastal wetlands. Salt, brackish and fresh marshes as well as mangrove and other swamps would be 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 would be impaired during the transitional period and their biodiversity may decrease. Although many wetlands have kept pace or have increased in area under the historic rate of sea-level rise owing to sediment entrapment and peat formation, vertical accretion of wetlands has not been observed to occur at rates comparable to those projected for sea-level rise in the next century.

6.0.18 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, although little of that productivity may be available to marsh animals and coastal fisheries. Over half the species of commercially important fishes in the southeastern US use salt marshes as nursery grounds. Wetlands also serve as sinks for pollutants and provide a degree of protection from floods, storms and high tides. Based on these functions, marshes can provide a present value to society of as much as $US5,500/acre or over $US10,000/ha.

6.0.19 Coastal wetlands and estuaries are important to many species. If sea-level rise is too rapid, natural succession of the coastal ecology will not take place and will lead to great disruption in life cycles. In the short term, production of fisheries could rise as marshes flood, die and decompose, thus improving fisheries habitat in some cases and providing more nutrients. Further nutrients will become available from the leaching of soils and peat which become more frequently flooded. This temporary increase in productivity appears to be happening now in the southeast US where sea-level rise is compounded by land subsidence. 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 is likely to be negative.

6.0.20 While considering potential changes in the biogeochemical cycles of chemicals from sea-level rise, it should be noted that (i) growth of nitrogen and phosphorus concentrations on a regional scale (in subpolar and mid latitudes, in the Bering Sea in particular) would result from flooding of coastal areas and from soil erosion; and (ii) many pesticides which are presently held in sediments could be released into the marine environment by coastal flooding.

6.0.21 The combination of climatic changes will cause coastal ecosystems to move inland, unless humankind intervenes, and poleward. Also, if sea-level rise is rapid, as predicted, productivity will probably fall, but there may be some decades during which wetlands-based productivity increases before it falls. Once the ocean begins to stabilize at its new level (if this were to occur in the foreseeable future), productivity will begin to decrease.

### *Inundation and recession of barrier islands, coral atolls and other shorelines*

6.0.22 Sea-level rise would cause inundation and recession of all types of shorelines, especially low-lying coastal areas. Many beaches have very small gradients of 1:100 or less. A 1 m rise in sea-level would inundate 100 m of beach. Additional shoreline recession would result from normal erosive processes including storm surges and wave attack. The potential destruction of coral atolls is perhaps most significant, because these island areas serve both as contained human habitats as well as important ecological habitats with high biodiversity. Unlike continental areas with receding coastlines, where areas for resettlement are available landward of the coasts, coral islands have very limited possibilities. If the rate of sea-level rise exceeds the maximum rate of vertical coral growth (8 mm/yr), then inundation and erosive processes begin to dominate, leading to the demise of the coral atoll. However, if the rate of sea-level rise is small, then coral growth may be able to keep pace. Although there are engineering solutions for retarding erosion and protecting against storm damage of continental coasts, coral atolls cannot be effectively protected.

6.0.23 Barrier beaches are important for human use, both for subsistence and recreation, and as protection for lagoons and mainland areas from coastal storms. Coastal areas have always been hazardous. Societies have adapted to or sought to control the most extreme conditions resulting from natural climate variability. The loss of habitable coastal areas, which are typically densely populated will undoubtedly lead to large-scale resettlement. Since most commercial and subsistence fisheries are de facto located in the very same vulnerable areas, the impacts are twofold: reduction in ecological (wetlands) habitat that sustains fish populations, coupled with increased threats to habitable coastal areas. Many areas around the globe, comprising thousands of kilometres of shoreline and affecting millions of people would be adversely affected by a rise of 1 m, or even 0.5 m. For the most part, prevention of the primary physical effects is not economical for most of the threatened coastline. Therefore, the prospect for adverse impacts should be considered to be extremely important and virtually irreversible.

## *Impacts on the World Ocean*

6.0.24 Global climate warming can change the physical, chemical and biological processes in the oceans, and affect productivity of the oceans and fisheries. Effective $CO_2$ doubling could lead to an increase of sea-surface temperature by 0.2°—2°C and to changed heat balance components. Impacts will differ among geographic zones.

6.0.25 In addition, an increase in atmospheric $CO_2$ could cause an increase in sea-water acidity up to 0.3 pH and elevation of the lysocline (because of solution of additional amounts of $CaCO_3$). These processes might be accompanied by a decrease in the stability of the complexes of trace metals with aquatic humus, strengthening the toxic impacts of these substances on marine organisms as well as a change in the conditions of accumulation of deposits.

6.0.26 Coastal ecosystems will be exposed to the most severe impact owing to a water temperature increase and, especially, to sea-level rise. Disturbances by hydrological and hydrochemical conditions in these regions will be accompanied by a shift of feeding zones of many commercial fish species and benthic organisms, a change in the trophic structure of coastal communities and, as a consequence, a decrease in their productivity. At the first stage, as the flux of nutrient increases, in the process of land flooding, a certain increase in the productivity of coastal areas might be observed.

6.0.27 A change in heat balance and the circulation system in the oceans will produce a direct effect on the productivity of marine ecosystems. Taking into consideration the fact that 45% of the total annual production is in the zones of oceanic and coastal upwellings and subpolar regions, a change in these regions would determine the future productivity of the oceans.

6.0.28 According to the results of numerical experiments with the use of General Circulation Models of the atmosphere-ocean system, as well as palaeo-oceanographical data, the global warming would be accompanied by a weakening of the intensity of oceanic upwellings because of a decrease in the meridional temperature gradient. This process will involve a decrease in the productivity of these ecosystems. However, some increase in the intensity of coastal upwellings as a result of increasing temperature difference between land and water surface, would partially compensate for the reduction of oceanic upwellings. Besides, an increase in the temperature at high latitudes will be accompanied by an increase in their productivity. As a result of the above changes, a redistribution of productive zones will probably occur. This could lead to disturbances in the trophic structure of marine ecosystems and to a change in the conditions of the formation of the stocks of commercial fishes.

6.0.29 An increase in the zone of the area of warm equatorial and tropical waters would cause the movement of pelagic and benthic communities of these areas to the boreal and temperate regions. This circumstance might significantly affect the structure of world fisheries. Under conditions of climate warming, the intensification of biodegradation processes will occur by up to 30—50% in the zone of high latitudes. This factor, along with the expected increase of ultraviolet-B radiation, resulting from the depletion of the ozone layer, could accelerate bacterial and photochemical degradation of pollutants and reduction of their 'residence time' in the marine environment. Ecological and biological consequences of climate changes will vary among geographic zones. A regional approach is needed to study the biogeochemical carbon cycle, especially in the most productive and vulnerable ecosystems of the ocean.

6.0.30 The highly productive subpolar and polar ecosystems of the Bering Sea, Arctic Seas and Southern Ocean are important to study because the high-latitude areas will see the greatest changes. These areas are important to the total global carbon cycle in the ocean, in climate-forming processes, in fisheries, and in marine mammal and bird production.

6.0.31 International investigations, for example those planned for the region of the Bering Sea, will contribute to the determination of the role of subpolar ecosystems in the formation of earth's climate, as well as to a more comprehensive study of possible ecological impacts of global warming on the ocean, in particular on fisheries.

6.0.32 Many fisheries and marine mammal populations are heavily stressed from fishing pressure. Climate changes will increase stress and the chance of collapse. However, for some species, the new climate may be more advantageous to their wellbeing.

6.0.33 One benefit of warming will be the reduction of sea ice and thus improved access for shipping. However, there are ecological concerns. Land animals use sea ice for migratory and hunting routes, while for many species of marine mammals (e.g. seals, polar bears, penguins) sea ice is an essential part of their habitat. Thus, reduction of the amount or duration of ice can cause difficulties for such animals. Moderate rises in sea-level, provided they are insufficient to threaten port installations, may prove to be beneficial by increasing the allowable draught of ships in shallow ports and channels.

### *Recommendations for action*

- Identification and assessment of the risks to coastal areas and islands and living resources of a 0.3—0.5 m rise in sea-level.

- Assessment of potential leaching of toxic chemicals with sea-level rise.

- Improvement of the methods for analyzing the major components of oceanic branch of carbon cycle (the carbonate system and organic carbon).

- Assessment of the possible impacts of increased UV-B radiation from stratospheric ozone depletion on oceanic and estuarine ecosystems.

- Determination of ecological impacts of Arctic and Antarctic sea ice reductions.

- Development of methodologies to assess the impacts on living marine resources, and socioeconomic impacts, of changes in the ocean and coastal zones.

- Development and implementation of multinational systems to detect and monitor expected environmental and socioeconomic impacts of ocean and coastal zone changes.

## 7. Impacts of climate change on seasonal snow cover, ice and permafrost, and socioeconomic consequences

### *Major findings*

7.0.1 Major findings are:

- The global areal extent and volume 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.

- Thawing and reduction in the areal extent of the terrestrial cryosphere can enhance global warming (positive feedback on climate warming) through changes in the global and local radiation and heat balances, and the release of greenhouse gases. This positive feedback could increase the rate of global warming and, in some regions, could result in changes that are sudden rather than gradual. The possibility of relatively rapid changes, increases the potential significance of the associated impacts.

- 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 in the Arctic and Antarctic possibly experiencing increases in seasonal snow cover.

- Decreases in seasonal snow cover can have both positive and negative socioeconomic consequences owing to impacts on regional water resources, winter transportation and winter recreation.

- Globally, the ice contained in glaciers and ice sheets is projected to decrease. Regional responses, however, are 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. Enhanced melt rates of glaciers may initially increase the flow of melt-waters; however, flows will decrease and eventually be lost as glacial ice mass decreases. Glacial recession and loss of ice from ice sheets will also contribute to sea-level rise.

- Degradation of permafrost is expected with an increase in the thickness of the seasonal freeze-thaw (active) layer and a recession of permafrost to higher latitudes and higher altitudes. The thickness of the active layer is expected to increase by 1 m over the next 40—50 years. Although major shifts are expected in climatic zones, recession of permafrost will significantly lag behind, receding only 25—50 km during the next 40—50 years. These changes could lead to increases in terrain instability, erosion and landslides in those areas which are currently underlaid by permafrost.

- The socioeconomic consequences of these changes in permafrost could be significant. Ecosystems which are underlaid by permafrost could be substantially altered owing to terrain disturbances and changes in the availability of water. The integrity of existing and planned structures and associated facilities and infrastructure could be reduced by changes in the underlying permafrost. Retrofitting or redesigning would be required at a minimum; however, in some situations the associated terrain disruptions and/or costs (environmental, social and economic) may be too large, necessitating abandonment. Development opportunities could also be affected in areas where the risks associated with developing in an area susceptible to permafrost degradation are assessed as too high.

- The terrestrial cryosphere, because of its relative responsiveness to climate and climatic changes, provides an effective means of monitoring and detecting climatic change.

- Lack of sufficient data and gaps in the understanding of associated processes limits more quantitative assessments at this time.

## *Principal issues*

7.0.2 The terrestrial component of the cryosphere consists of seasonal snow cover, mountain glaciers, ice sheets, and frozen ground, including permafrost and seasonally frozen ground. These elements of the terrestrial cryosphere currently cover approximately 41 million $km^2$, with seasonal snow cover covering as much as 62% of the Eurasian continent and virtually all of North America north of 35° latitude.

7.0.3 Projected changes in climate will dramatically reduce the areal extent and volume of these elements of the terrestrial cryosphere. This has implications not only with respect to changes in the availability of fresh water, changes in sea-level and in terrain characteristics, but also for societies and related economic systems which have come to depend on, or are limited by, the existence of a terrestrial cryosphere.

7.0.4 Feedback mechanisms are an important factor in understanding the impacts of climatic change on the terrestrial cryosphere. Reduced areal coverage of these elements and degradation of permafrost as a result of climatic warming can enhance warming through changes in surface characteristics and release of greenhouse gases.

7.0.5 The impacts of socioeconomic consequences of changes in the terrestrial cryosphere will depend to a large extent on the rate at which the changes occur. Where the rate of change is quick or sudden, environment and associated social and economic systems will have little time to adapt. Under these circumstances the impacts and socioeconomic consequences could be large.

## *Seasonal snow cover*

7.0.6 General Circulation Models indicate that in most parts of the Northern and Southern Hemispheres the area of snow cover is expected to decrease as a result of increased temperature and, in most regions, a corresponding decrease in total mass of the snow. Areas where snow cover is projected to increase include latitudes south of 60°S and higher elevations of inland Greenland and Antarctica (though the latter is, and will remain, largely a cold desert).

7.0.7 A reduction in the areal snow coverage and in the length of the snow cover season will result in a positive climatic feedback, increasing global warming as a result of the greater amount of solar radiation that a snow-free surface can absorb relative to one that is snow-covered.

7.0.8 Loss of snow cover has both negative and positive socioeconomic consequences. Decreases in snow cover will result in increased risks of damages and losses for those systems which rely on snow as protection (ie insulation) from cold winter climates. Included are agricultural crops such as winter wheat, trees and shrubs, hibernating animals, and construction and maintenance of municipal infrastructures.

7.0.9 Reductions in both the temporal and spatial coverage of seasonal snow cover will have significant ramifications for water resources as the amount of water available for consumptive (e.g. potable and irrigation water) and non-consumptive (e.g. hydroelectric power and waste management) uses decreases. Particularly sensitive are those areas such as the Alps and Carpathians, the Altai mountains of Central Asia, the Syr Dar'ya and Amu Dar'ya region of the USSR, the Rocky Mountains and the North American Great Plains, all of which are dependent on snowmelt for the majority of their spring and summer water resources.

7.0.10 Changes in snow cover will also affect tourism and recreation-based industries and societies, particularly winter recreation sports such as skiing. Projected climate change could eliminate a $50 million per annum ski industry in Ontario, Canada.

7.0.11 From a positive impacts perspective, reductions of seasonal snow cover will reduce expenditures on snow removal and will increase access opportunities and ease transportation problems. A reduction in snow cover, however, will also have adverse impacts for transportation in those areas which rely on snow roads in winter. Inability to use snow roads will result in the necessity of using other more costly methods of transportation.

## *Ice sheets and glaciers*

7.0.12 The relationships between climate and ice sheets and glaciers are complex, and because of relatively limited monitoring and research, not fully understood at this time. Increased temperatures generally result in increased ablation and, hence, a decrease in ice mass. Conversely, increased snowfall usually increases ice mass. Since projected changes in climate for some ice-covered regions include both increases in temperature and snowfall, understanding the impact of climatic changes on glaciers and ice sheets must consider the combined impact.

7.0.13 The bulk of the earth's ice mass is stored in the Antarctic ice sheet, divided between an eastern portion resting on continental crust and a large western portion which is underlaid both by continental crust and ocean. Much of the remaining ice mass is contained in the Greenland ice sheet, with smaller quantities stored in glaciers throughout the world.

7.0.14 Although observed data are limited, it is estimated that both the Antarctic and Greenland ice sheets are at present roughly in equilibrium, with annual gains close to annual losses. There is some evidence that suggests that the Greenland ice sheet has been thickening since the late 1970s, which has been attributed to new snow accumulations on the ice sheet.

7.0.15 Greenhouse-gas-induced climatic change will tend gradually to warm these sheets and bring them out of balance with the new climate regime. Change in ice-sheet volume is likely to be slow, however, with significant loss unlikely to occur until after 2100. Calculations for Greenland suggest that a 3% loss of ice volume in the next 250 years is possible, based on the projected changes in climate. In the case of the Antarctic ice sheet the situation is more complex. The mass of the eastern ice sheet is expected to remain virtually the same or increase slowly as a result of expected increases in precipitation and temperatures. In contrast, the western ice sheet, like other marine ice sheets is inherently unstable.

7.0.16 Climatic warming could cause groundline retreat and rapid dispersal of ice into the surrounding ocean by way of relatively fast-flowing ice streams. These changes in behaviour could lead to collapse of a portion of the western Antarctic ice sheet which, depending on the amount of ice involved, could have a dramatic impact on sea-level and the surrounding environment.

7.0.17 The response of glaciers to climatic change will depend on their type and geographic location. In general, however, they have been shrinking for the last 100 years and are expected to continue to do so in response to projected changes in climate. In Austria a 3°C warming by 2050 is projected to cause a reduction by about one-half in the extent of alpine glaciers. Melting of glaciers in the Soviet arctic archipelagoes may result in their disappearance in 150—250 years. In contrast, an assessment of mountain glaciers in the temperate zone of Eurasia indicates that up to 2020 these glaciers will, in general, remain essentially unchanged, with increased precipitation compensating for increased melt.

7.0.18 Ice sheet and glacier melting will result in higher sea-levels. Observations over the last century indicate that levels have been rising between 1 and 3 mm/year primarily as a result of mass loss from alpine glaciers. Current projections suggest an accelerated rise with greenhouse gas warming to a most probable rise of 65 cm by the end of the next century.

7.0.19 Glacial melting can act as a negative feedback to regional and global warming, with heat extracted from the air to melt glacial ice and snow, thereby reducing the degree of warming.

7.0.20 The melting of glaciers will also alter regional hydrologic cycles. In New Zealand it has been estimated that a 3°C increase in temperature would, in the short term, increase glacier-fed river flow in some western rivers, increasing hydroelectric power generation by 10%. Another effect of glacier retreat is possible increased debris flows. Large amounts of debris masses on steep slopes will become exposed as a result of glacial retreat and, therefore, would be unstable and vulnerable to the effects of erosion. Landslides would result, leading to burial of structures, traffic routes and vegetation. Obstructions of river flows and increased sediment loads resulting in changes in water quantity (e.g. local floods and reduced flows downstream) and water quality would also be likely to occur as a result of debris flows.

## *Permafrost*

7.0.21 Permafrost is the part of the terrestrial cryosphere consisting of ground (soil and rock) that remains at or below freezing throughout the year. It usually contains ice which can take a variety of forms from ice held in soil pores to massive bodies of more or less pure ice many metres thick. The presence of this ice in the ground makes it behave uniquely as an earth material, and makes its properties vulnerable to climatic warming.

7.0.22 At present about 20—25% of the land surface of the earth contains permafrost, primarily in the polar regions but also in the alpine areas at lower latitudes. It occupies approximately 10.7 million $km^2$ in the USSR, 5 million $km^2$ in Canada, 2 million $km^2$ in China and 1.5 million $km^2$ in Alaska. Present and past climate is the major determinant of permafrost occurrence and characteristics; however, a variety of other factors is also important, for example, the properties of the soil, and overlying terrain, vegetation and snow cover.

7.0.23 Permafrost is usually present where the mean annual air temperature is less than -1°C. At temperatures near this value it is discontinuous in extent (discontinuous permafrost zone). Both its extent and thickness increase at progressively higher latitudes where temperatures are lower. It has been found to extend to depths of approximately 1000 m or more in parts of Canada, approximately 1500 m in the USSR and 100—250 m in China.

7.0.24 Permafrost can also exist in seabeds. There is extensive ice-bound material in the continental shelf beneath the Arctic Ocean; however, this permafrost is commonly relict (ie it formed under past conditions and would not form under current ones).

7.0.25 Permafrost is to a large extent inherently unstable since it exists so close to its melting point. Most responsive to changes in climate would be those portions nearest the surface. Climate warming would thicken the active layer, leading to a decrease in soil stability. This permafrost degradation would lead to thaw settlement of the surface (thermokarst), ponding of surface water, slope failures (landslides) and increased soil creep. This terrain instability would result in major concerns for the integrity and stability of roads, pipelines, airfields, dams, reservoirs and other facilities in areas which contain permafrost. Terrain instability of the surface layer can also occur as a result of permafrost degradation in alpine areas, such as the Alps. This instability could result in dangerous debris falls from thawed rocks and mudflows.

7.0.26 Slope failures, thermokarst and loss of near-surface moisture, as the increased depth of the active layer moved limited water supplies further from the surface, would have detrimental effects on vegetation and could lead to significant decreases in plant populations. In the longer term, permafrost degradation would allow the growth of deeper rooted, broadleaved species and the establishment of denser forest of coniferous species. Wildlife could also be affected through changes in terrain, surface hydrology and food availability. Loss of species and habitats can be expected, especially where wetlands dry out or areas are flooded as a result of melt.

7.0.27 Assessment of the effects of climate change on permafrost in any particular location must consider factors other than temperature, e.g. changes in summer rainfall and snow cover. In general, however, the projected warming during the next several decades would significantly deepen the active layer and initiate a northward retreat of permafrost. It is expected that a 2°C global warming would shift the southern boundary of the climatic zone currently associated with permafrost over most of Siberia north and northeast by at least 500—700 km. The southern extent of permafrost will lag behind this, moving only 25—50 km in the next 40—50 years (up to 10% reduction in an area underlaid by continuous permafrost). The depth of the active layer is expected to increase by 1 m during the next 40—50 years. Projected changes in permafrost in Canada are of similar magnitude.

7.0.28 The melting of permafrost would result in the release of methane and, to a lesser extent, $CO_2$ from previously frozen biological material and from gas hydrates. The extent to which this will enhance the greenhouse effect is uncertain, but could be about 1°C by the middle of the next century.

7.0.29 The socioeconomic impacts of permafrost degradation will be mixed. Maintenance costs of existing northern facilities such as buildings, roads and pipelines will tend to rise with abandonment and relocation needed in some cases. Changes in current construction practices will be necessary, as may be changes in sanitary waste disposal. Benefits from climate warming and permafrost melt are likely for agriculture, forestry, and hunting and trapping.

### *Recommendations for action*

7.0.30 Projected greenhouse-gas-induced changes in climate will lead to ablation of global ice masses. Uncertainty exists, however, regarding how this global response will be reflected at the regional/local level and how the individual ice masses and seasonal ice and snow will respond. The most important effects of climatic change at high latitudes and elevated regions will be on and through changes in the terrestrial cryosphere. Furthermore, the terrestrial cryosphere is particularly suited for early detection of the effects of climate change. These two points necessitate a better understanding of the nature and dynamics of these ice masses and the factors that control them. This will require:

- establishment or enhancement of integrated, systematic observation programmes commensurate with research on the use of more efficient ground-based systems and remote sensing technologies designed to provide baseline information and trends;
- concurrent monitoring of those facilities, structures and natural resources that are at risk owing to projected changes in the terrestrial cryosphere;
- establishment of new guidelines and procedures for design and construction practices that consider the impacts of climatic changes on permafrost;
- research, including international cooperative efforts, on the relationships between components of the terrestrial cryosphere and climate in conjunction with other determining factors, including feedback mechanisms;
- refinement of existing climate-terrestrial cryosphere models;
- impacts assessments nationally and regionally that will provide data and information on the impacts of climate change on areas in which components of the terrestrial cryosphere occur and the resulting socioeconomic consequences;
- assessment of the needs for protected areas (natural reserves) for affected species and habitats; and
- development and distribution of relevant educational material and information on climatic changes, their impacts on the terrestrial cryosphere and socioeconomic consequences, as well as a wider distribution of research results.

# 8. Summary of major future actions

8.0.1 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;

- a 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.

# 9 Concluding remarks

9.0.1 Human-induced climate change can have profound consequences for the world's social, economic and natural systems. Each country should take steps to understand the impacts on its population and land resources resulting from such a change, and the consequences of sea-level rise, the changed character of atmospheric circulation and the resulting changes in typical weather patterns, reduction of freshwater resources, increased ultraviolet-B radiation and spreading of pests and diseases. These can affect the potential of food and agricultural production and adversely affect human health and well-being.

9.0.2 Too rapid a change in climate may not allow species to adapt and, thus, biodiversity could be reduced. This reduction could occur equally as well in the cryosphere regions, where melting of sea ice could accelerate, and in the equatorial regions where sea surface temperatures could increase. Traditional cost-benefit analyses do not allow for assessment of these risks. Although substantial scientific uncertainty remains concerning the precise time, location and nature of particular impacts, it is inevitable, under the scenario developed by Working Group I, that in the absence of major preventive and adaptive actions by humanity, significant and potentially disruptive changes in the earth's environment will occur.

9.0.3 The world community recognizes the need to undertake certain actions to reduce and mitigate the impact of climate change. Specific measures should follow the assessments of potential impact on the biosphere and on human activity, and a comparison of the net costs of adaptation and mitigation measures. Some of these impacts, such as sea-level rise, are likely to proceed slowly but steadily while others such as shifts in climate zones—which will affect the occurrence of such events as floods, droughts and severe storms—may occur unpredictably. Regions and nations differ considerably in their vulnerability to such changes and subsequent impacts. Generally human activity in developing countries is more vulnerable than that in developed countries to the disruption associated with climate change. Global warming and its impact must not widen the gap between developed and developing countries.

9.0.4 The capacity of developing nations to adapt to likely climate changes and to minimize their own contributions to it through greenhouse gas emissions, is constrained by their limited resources, by their debt problems and by their difficulties in developing their economies on a sustainable and equitable basis. These countries will need assistance in developing and implementing appropriate response options (including consideration of technological development and transfer, additional financial assistance, public education and information). As they possess greater resources to cope with climate change, developed countries must recognize the need to assist developing countries to assess and deal with the potential impacts of climate change.