D

Vulnerability to sea-level rise

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

World oceans and coastal zones: ecological effects
Terrestrial component of the cryosphere

VII World oceans and coastal zones: ecological effects

Co-Chairs and Lead Authors

A Tsyban (Russia)
J Everett (USA)
M Perdomo (Venezuela)

Contributors

D Albritton (USA)
A Bakun (USA)
T Bigford (USA)
M Cole (USA)
D Dey (USA)
D Dow (USA)
B Glebov (Russia)
P Kaplin* (Russia)
M Korsak (Russia)
A Kulikov (Russia)
V Mamaev (Russia)
G Maul* (USA)
D Mountain (USA)
G Panov (Russia)
C Peterson (USA)
J Scheraga (USA)
R Reed (USA)
K Trenberth (USA)
J Whitledge (USA)
S Zeeman (USA)

* Special recognition

VII World oceans and coastal zones: ecological effects

1 Regional ecological impacts of climate change

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

2 Impacts of rises in temperature

2.1 *Arctic and subarctic region*

The earlier IPCC Impact Assessment provided information on expected physical changes in arctic and subarctic region systems. More physical and biological information is now available. Even the IPCC scenario for climate warming and the attendant reduction in the ocean ice cover may cause a more than tenfold increase of carbon influx in the Eurasian and Canadian basins of the Arctic Ocean to 1.4×10^9 kg C/year. This can be compared with the general anthropogenic emission of CO_2 to the atmosphere of 5×10^9 kg C/year. In the Bering Sea, for example, the IPCC scenario, along with the intensification of continental and shelf ice melting, will lead to significant increases in river inflow, an average salinity decrease by 0.5–1.0 part per thousand (with greatest reductions in nearshore Alaskan waters), increased turbidity with more suspended particles, a shift northward of surface isotherm of more than 50 km per 0.5°C rise in temperature, and an alteration of the oceanic current system as a result of changes in river flows.

An increase of the vegetative season duration by 1–2 weeks should lead to an annual primary production increase of 5–10%, with an increase of 1.2% in secondary production, elimination of 8–12% more organic matter from the photic layer through biosedimentation, and bacterial decomposition of organic matter will increase. It is estimated that the minimal increase in absorption of atmospheric CO_2 by the Bering Sea each year will grow from about 50×10^9 kg C/year to about 62×10^9 kg C/year.

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

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

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

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

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

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

2.2 *Tropical/subtropical regions*

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

In the sense that Lamb (1987) develops climate change scenarios as plausible future events, Gray (1992) argues for the following likely effects (cf Gallegos et al. 1992; Aparicio 1992; Wigley and Santer 1992): rainfall will continue to decrease, air temperatures will continue to rise, surface wind speed will continue to increase, and evaporation will increase. Caution must be exercised in interpreting these changes as anything other than 'persistence forecasting'. It is not known, for example, if the decreased frequency of large hurricanes over the last two decades is really a long-term trend or part of some cycle as yet not understood. Hurricanes are an important contributor of rainfall; is the decrease in precipitation merely a reflection of fewer large storms? Increased temperature may affect the drag of wind on water, but Mercado et al. (1992) and Hendry (1992) see no clear indication of significant change in storm surges or waves associated with elevated temperature.

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

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

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

3 Impacts of sea-level rise

3.1 Bering Sea

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

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

3.2 Caribbean/Gulf of Mexico/Bahamas region

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

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

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

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

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

3.3 Southeast Asia region

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

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

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

3.4 Summary

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

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

4 Case study areas in progress

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

5 Recent findings and updates

5.1 Ultraviolet (UV-B) radiation

The IPCC Impacts Assessment expressed concern about the possible effects of increasing irradiance of UV-B on marine ecosystems. New findings of the WMO/UNEP (1991) indicate that UV-B radiation reaching oceanic and coastal zone environments will increase faster than expected. Since so many marine resources spend all (or vulnerable parts) of their lives near the water surface, the urgency of our concern over genetic changes and direct harm to plant and animal life is heightened accordingly.

Solar radiation bleaches cellular pigments of freshwater and marine phytoplankton and also impairs motility and photomovement of the plankton. The marine phytoplankton communities represent by far the largest ecosystem on earth. Therefore, even a small percentage decrease in population would result in important losses in the biomass productivity of the ocean. Any decrease in the phytoplankton populations will decrease the sink capacity for atmospheric CO_2 and will change the carbon biogeochemical cycling in the marine environment.

5.2 Coastal contamination

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

5.3 Storm intensity/frequency

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

5.4 Coastal structures

The assessment that most wetland loss accompanying sea-level rise would be due to inundation and not to protective coastal structures is reaffirmed; it is also recognised that much of the inundation effect could be an indirect result of structures built to combat coastal sea-level rise (Hendry 1992; Parry et al. 1991). For example, the construction of weirs to prevent saltwater intrusion into wetlands, or the construction of levées along rivers/wetland boundaries to prevent flooding, can lead to impounding of water, development of anaerobic conditions and sulphide build-up in marsh soil which can be accompanied by the death of the wetland vegetation and land loss (Mendelssohn and McKee 1988). The weirs accomplish this by directly controlling water levels, while the levées can achieve the same result from backwater flooding. Weirs can also prevent the movement of living marine resources from wetland nurseries into the adjacent coastal waters (Knudsen et al. 1989).

6 Research and monitoring needs

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

6.1 Monitoring

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

6.2 Methods

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

6.3 Ultraviolet-B radiation

- Determine the susceptibility of marine organisms to increasing amounts of UV-B radiation and the quantitative impacts of these effects on marine ecology, on fisheries and on marine carbon cycling;

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

6.4 *Modelling*

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

6.5 *International programs*

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

6.6 *Ecological research*

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

7 Recommendations

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

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

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

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

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

References

Aparicio, R. 1992. 'Meteorological and oceanographic conditions along the southern coastal boundary of the Caribbean Sea', Chapter 3.2, in: *Climatic changes in the Intra-American Sea,* G.A. Maul (ed.), Edward Arnold Publishers (in press).

Bernal, P. H. 1991. 'Consequences of Global Change for Oceans: A Review', *Climatic Change* 18: 339–359.

Childers, D.L., Day Jr., J.W. and Muller, R.A. 1990. 'Relating climatological forcing to coastal water levels in Louisiana estuaries and the potential importance of El Niño-Southern Oscillation events', *Climate Research* 1: 31–42

Dennis, K.C., Nicholls, R.J. and Leatherman, S.P. 1991. *Coastal Land Loss Studies: Reconnaissance Level Survey.* U.S. Environmental Protection Agency.

Ellison, J.C. and Stoddart, D.R. 1991. 'Mangrove ecosystem collapse during predicted sea-level rise: Hologene analogues and implications', *J. Coastal Res.*, 7(1): 151–165.

Gallegos, A., Czitron, S., Zavala, J. and Fernandez, A. 1992. 'Scenario modelling of climate change on the ocean circulation of the Intra-American Sea', Chapter 2.2 in G.A. Maul (ed.), op. cit.

Gray, C.R., 1992. 'Regional meteorology and hurricanes', Chapter 3.1 in G.A. Maul (ed.) op. cit.

Hanson, K. and Maul, G.A. 1992. 'Analysis of temperature, precipitation and sea level variability with concentration on Key West, Florida for evidence of trace-gas induced climate change', Chapter 3.5 in G.A. Maul (ed.) op. cit.

Hendry, M. 1992. 'Sea level movements and shoreline changes', Chapter 3.3 in G.A. Maul (ed.) op. cit.

IPCC, 1990a. *Climate Change: The IPCC Impacts Assessment*, Australian Government Publishing Service, 268 p.

IPCC, 1990b. *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, 339 p.

Knudsen, E.E., Paille, R.A., Rogers, B.D., Herke, W.H. and Geaghan, J.P. 1989. 'Effects of a fixed-crest weir on brown shrimp *Penaeus aztecus* growth, mortality and emigration in a Louisiana coastal marsh', *North Amer. Jour. Fish. Manage.*, 9: 411–419.

Lamb, P.J. 1987. 'On the development of regional climatic scenarios for policy-oriented climate-impact assessment', *Bull. Amer. Meteorol. Soc.*, 68(9): 1116–1123.

Mendelssohn, I.A. and McKee, K.L. 1988. '*Spartina alterniflora* dieback in Louisiana: time-course investigation of soil waterlogging effects', *Jour. Ecology*, 76: 509–521.

Mercado, A., Thompson, J. D. and Evans, J.E. 1992. 'Requirements for modelling of future storm surge and ocean circulation', Chapter 2.3 in G.A. Maul (ed.) op. cit.

Milliman, J.D. 1992. 'Impact on coral reefs', Chapter 4.4 in G.A. Maul (ed.) op. cit.

Muller-Karger, F.E. 1992. 'River discharge variability including satellite-observed plume dispersal patterns', Chapter 3.4 in G.A. Maul (ed.) op. cit.

Parry, M.L., Magalhaes, A.R., and Ninh, N.H. (eds.) 1991. *The potential socio-economic effects of climate change,* UNEP, Nairobi, 26 pages + appendices.

Shapiro, L.J. 1988. 'Impact of climate change on hurricanes', in: *Implications of climatic changes in the Wider Caribbean Region*, UNEP(OCA)/CAR WG.1/ INF.3, 187 pages.

Snedaker, S.C. 1992. 'Impact on mangroves', Chapter 4.3 in G.A. Maul (ed.) op. cit.

Swenson, E.M. and W.S. Chuang 1983. 'Tidal and subtidal water volume exchange in an estuarine system', *Estuarine, Coastal and Shelf Science*, 16: 229–240.

Valiela, I. and Costa, J.E. 1988. 'Eutrophication of Buttermilk Bay, a Cape Cod coastal embayment: concentrations of nutrients and watershed nutrient budgets', *Environ. Manag*, 12: 539–553.

Vincente, V.P., Singh, N.C., and Botello, A.V. 1992. 'Ecological implications of potential climate change and sea level rise', Chapter 4.2 in G.A. Maul (ed.) op. cit.

Wigley, T.M.L, and Santer, B.D. 1992. 'Future climate of the Caribbean Basin from Global Circulation Models', Chapter 2.1 in G.A.Maul (ed.) op. cit.

Williams, E.H., Jr., Goenaga, C., and Vicente, V. 1987. 'Mass bleaching on Atlantic coral reefs', *Science*, 238: 877–878.

WMO/UNEP (1991) *Scientific Assessment of Ozone Depletion.*

VIII Terrestrial component of the cryosphere

Lead Authors:
P A Melnikov (USSR)
R B Street (Canada)

Expert Contributors:
R G Barry (USA)
M Brugman (Canada)
N Grave (USSR)
Cheng Guodong (China)
A E Corte (Argentina)
T H Jacka (Australia)
A S Judge (Canada)
R M Koerner (Canada)
E A Koster (The Netherlands)
V J Lunardini (USA)
D A Robinson (USA)
V Volgina (USSR)

VIII Terrestrial component of the cryosphere

1 Background

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

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

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

2 Progress since the IPCC Impacts Assessment in 1990

2.1 Snow cover

Recent analyses (Cess et al. 1991) of the differences in the behaviour of General Circulation Models (GCMs) suggest that snow feedbacks include both the simple, direct positive feedback and indirect negative affects. The positive feedback hypothesis suggests that a decrease in snow cover makes the earth less reflective, causing it to warm as it absorbs more solar radiation and reflects less back out to space. Recent analyses reveal that some models suggest that clouds could redistribute themselves to cover those areas which were covered with snow thus reducing to some degree the positive feedback. Some of the models also suggest that decreases in snow cover could increase the amount of long-wave radiation emitted at the top of the atmosphere, which would lead to cooling of the Earth.

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

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

2.2 Permafrost

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

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

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

Anisimov and Nelson (1990) and Stuart and Judge (1992) have used the frost index model to examine the circumpolar distribution of permafrost and to compare it for Eurasia and Amerasia. The advantage of the frost index is that it accounts for and couples both temperature and precipitation (snow cover). Further calculations have examined the change as predicted by the various GCMs.

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

Studies of the isotope chemistry of carbon in the atmosphere suggests that up to 30% derives from old carbon (or earth) sources. In the tundra and northern taiga ecosystems there is an abundant reserve of carbon stored in moss, peat, and soil duff. The potential release of this carbon as a result of global warming and the associated increase in soil temperatures, increasing depth of the seasonal thaw layer, and improved drainage suggest increases in CO_2 emissions from these regions as a result of global warming. Currently, CO_2 data from global systematic observations identifies a maximum of annual mean CO_2 concentrations over the tundra and northern taiga regions around 70°N latitude and not between 20–60°N where the greatest majority of the emissions from human activities occurs.

Recent experiments indicate that a sharp increase in CO_2 emissions from deep freezing soil monolits occurs by warming them 4°C. This conclusion is supported by the increase in emissions that is observed in April as the temperature of the upper horizon of frozen deposits increases from -8°C to -4°C.

Emissions of methane from the earth's surface are currently estimated at 540x1012 g/year including 35x1012 g/year from tundra areas (Khalil and Rasmussen 1990 and Melnikov 1991). The annual flow rate of methane into the atmosphere from present-day sources within permafrost regions in Russia are estimated to be 9.2x107 m^3 or 6.1x104 tonnes (Glotov, in press).

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

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

2.3 *Ice sheets*

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

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

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

Although the Southern Hemisphere record is not as detailed as that for the Northern Hemisphere, work by Ruddell (1990) has shown that several New Zealand glaciers have retreated since the mid 1800s. In particular, a decrease in the volume of the Tasman Glacier is attributed to a warming in the order of 0.75°C, accompanied by a decrease in precipitation of about 10% since the middle of the last century.

3 Information and data gaps

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

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

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

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

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

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

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

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

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

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

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

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

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

4 Responses to close information and data gaps

The collection, through internationally coordinated programs, of basic data on snow cover extent and volume, glacier behaviour, and permafrost temperatures, ice content and thickness is of utmost importance to improve our understanding and to improve models of climate-cryosphere relationships. Where possible, existing time-series of observations should be compared with recent and historical climate records to study the cryospheric responses to recent warming and specific climatological conditions. Current observational programs should be continued, while the extension of the global network with observations at new locations (particularly in the Southern Hemisphere) and by remote sensing (eg satellite, radar and photogrammetry) is strongly recommended.

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

4.1 Snow cover

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

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

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

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

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

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

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

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

4.2 Permafrost

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.3 Ice sheets

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

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

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

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

The gravity/GPS technique is presently being used on ice sheets in the Canadian Arctic and at seasonal Antarctic sites to detect elevation changes at the tops of ice sheet summits. Vertical (elevation) resolution also limits the use of satellite and GPS in areas where accumulation rates are low (ie <20 g cm2y-1) as changes in both the accumulation rate and elevation will be even lower.

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

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

The means of encouraging and, where necessary, facilitating the required support for these activities should be the subject of international dialogue. Specific requirements, recommendations, priorities and their implications (globally and regionally) including considering both the needs and resource (human and monetary) requirements should be the subject of this dialogue.

References

Allen, D.M., Michel, F.A. and Judge, A.S. 1988. 'The permafrost regime in the Mackenzie Delta, Beaufort Sea Region, NWT and its significance to the reconstruction of paleoclimatic history', *Journal of Quaternary Science*, 3, pp.3-13

Anisimov, A.O. and F.E. Nelson 1990. 'Applications of mathematical models to investigate climate-permafrost', *Meteorlogiyai Gidrologiya* 10 pp.13-20.

Archangelov, A.A. and Novgoroda, E.V. 1991. 'Genesis of marine ice at "Ice Mountain", Yenesei River; according to gas anayses', *Permafrost and Periglacial Processes* 2. pp.167-190.

Barry, R.G. 1990. 'Changes in mountain climate and glacio-hydrological response', *Mountain Res. Devel.*, 10:pp.161-170

Barry, R.G. 1991. 'Observational evidence in global snow and ice cover', in: M.E. Schlesinger (ed.) *Greenhouse-gas-induced climatic changes: A critical appraisal of simulations and observations.* Elsevier, Amsterdam. pp. 320-345

Bentley, C.R. and Giovinetto, M.B. 1991. 'Mass balance of Antarctica and sea level change', in: Proceedings of International Conference on the Role of Polar Regions in Global Change. Fairbanks, Alaska, June 1990 (Arctic Consortium of the United States)

Cess, R.D., G.L. Potter, M.-H. Zhang, J.-P. Blanchet, S. Chalita, R. Colman, D.A. Dazlich, A.D. Del Genio, V. Dymnikov, V. Galin, D. Jerrett, E. Keup, A.A. Lacis, H. Le Treut, X. -Z. Liang, J.-F. Mahfouf, B.J. McAcaney, V.P. Meleshko, J.F.B. Mitchell, J.-J. Morcrette, P.M. Norris, D.A. randall, L. Rikus, E. Roeckner, J.-F. Royer, U. Schlese, D.A. Sheinin, J. M. Slingo, A.P. Sokolov, K.E. Taylor, W.M. Washington, R.T.Wetherald, and I. Yagai. 1991. Interpretation of snow-climate feedback as produced by 17 general circulation models, Science, Vol.253 pp. 888-892

Clark, J.W., Armand P. and Matson M. 1986. 'Possible causes of plumes from Bennet Island, Soviet Far Arctic', *American Association Petroleum Geologists Bulletin*, 70, pp 574.

Collett, T.S., Bird K.J., Pkvenvolden K.A. and Magoon L.B. 1988. 'Geological interrelations relative to gas hydrates within the North Slope of Alaska', *USGS Open-File Report* 88-389, Menlo Park, California.

Glotov, V.E. in press. 'Permafrost and northern (peaty) lands: the source and place of accumulation of gases which cause the "greenhouse effect" (within the USSR land)', Contribution to: Permafrost and Periglacial Processes.

IPCC 1990. *Climate Change: The IPCC Impacts Assessment.* (WJ McG Tegart, GW Sheldon, DC Griffiths, eds) Australian Government Publishing Service. Canberra. 268pp.

Judge A.S., Tucker C.M. Pilon J.A., Moorman B.J. 1991 'Remote Sensing of Permafrost by Ground Penetrating Radar at Two airports in Arctic Canada', *Arctic* pp.40–48.

Khalil, M.A.K. and Rasmussen, R.A. 1990. 'Atmospheric methane: recent global trends', *Environmental Science and Technology*. 24. pp.619–634.

Koerner, R.M. 1989. 'Queen Elizabeth Island Glaciers', in: Chapter 6, Quaternary Geology of Canada and Greenland, ed. R.J. Fulton, *Geological Survey of Canada, Geology of Canada*, Volume k-1, p.464–477

Koerner, R.M. and Fisher,D.A. 1990. 'A record of Holocene summer climate from a Canadian High Arctic ice core', *Nature*, 343:6259, pp. 630–631

Koerner, R.M. and Brugman, M.M. 1991. 'Mass balance trends in the Canadian High Arctic and Western Cordilleran Glaciers over the past three decades', Paper presented IAMAP symposium 'Climate-dependent dynamics, energy and mass balance of polar glaciers and ice sheets', Vienna, August 1991. Abstract

Koster E.A. 1991. 'Assessment of climate change impact in high-latitudinal regions', *Terra* 103, pp. 3–13.

Kvenvolden, K.A., Lorenson, T.D. and Reeburgh, W.S. 1992. 'Methane in permafrost—Preliminary Studies at CRREL Permafrost Tunnel near Fox, Alaska', *EOS* pp119 (Abstract volume, AGU).

LaFleche P.T., Judge A.S., and Taylor A.E. 1987. 'Applications of Geophysical Methods to Resource Development in Northern Canada', *CIM Bulletin*, 80, pp.78–87.

Lingle, C.S., Brenner, A.C., Zwally, H.J., and DiMarzio, J.P. in press. 'Multi-year elevation changes near the western margin of the Greenland Ice Sheet from satellite radar altimetry', in: proceedings of the 'International Conference on the role of the Polar Regions in Global Change', University of Fairbanks, Alaska, August 1990.

Melnikov, P.I. 1991. A Brief Report of the 6th Subgroup of the Second Working Group IPCC: The Climate Warming and Permafrost. 3pp.

Morgan, V.I., Goodwin. I.D., Etheridge, D.M. and Wookey, C.W. 1991. 'Evidence from Antarctic ice cores for recent increases in snow accumulation', *Nature* 354 (6348): pp 58–60.

Neave K.G., Judge A.S., Hunter J.A., and MacAuley H.A. 1978. 'Offshore permafrost distribution in the Beaufort Sea as determined from temperature and seismic observations', *Geological Survey of Canada Paper* 78–1C, pp.13–18.

Nisbet E. 1990. 'Climate change and methane', *Nature* 347, pp.23.

Robinson, D.A. and Dewey. K.F. 1991. 'Recent variations in Northern Hemisphere snow cover', in: Proceedings of the 15th Annual Climate Diagnostics Workshop, NOAA.

Robinson, D.A., Keimig, F.T. and Dewey, K.F. 1991. 'Recent variations in northern hemisphere snow cover', in: Proc. Fifteenth Annual Climate Diagnostics Workshop, NOAA pp. 219–224.

Rozenberg G., Henderson J.D., Sartorelli A.N., and Judge A.S. 1985. 'Some aspects of transient electromagnetic sounding for permafrost delineation', Workshop on Permafrost Geophysics, US Army CRREL Special Report 85–5, 118p.

Ruddell, A.R. 1990. 'The glaciers of New Zealand's Southern Alps: A century of retreat', paper presented at ANZAAS Congress. Hobart, February 1990.

Stuart R.A., Etkin D.A. and Judge A.S. 1991. 'Recent observations of air temperature and snow depth in the Mackenzie Valley area and the implications on the stability of permafrost layers', *Canadian Climate Centre Report* 91-2, 178pp.

Stuart R.A. and Judge A.S. 1992. 'On the applicability of GCM estimates to scenarios of global warming in the Mackenzie Valley area', *Climatological Bulletin* 25 pp.148–169.

Taylor A.E. 1991. 'Marine transgression, shoreline emergence: evidence in sea-bed and terrestrial ground temperatures of changing relative sea-levels, Arctic Canada', *Journal of Geophysical Research* 96B4, pp. 6893–6909

Taylor A.E., Judge A.S. and Allen V. 1989. 'The automatic well temperature measuring system installed at Cape Allison C-47, offshore well, Arctic Islands of Canada. Part 2—data retrieval and analysis of the thermal regime', *Journal of Canadian Petroleum Geology*, 28 pp.95–101.

Todd et al. 1992 Zwally, H.J., Brenner, A.C., Major, J.A., Bindschadler, R.A. and Marsh, J.G. 1989. 'Growth of the Greenland Ice Sheet: Measurement', *Science*, 246, p. 1587–1589