CLIMATE CHANGE: HIGH-LATITUDE REGIONS

E. F. ROOTS
Department of the Environment, Ottawa, Canada, K1A OH3

Abstract. The distinctive physical setting of high-latitude regions results not only in enhanced change in mean surface temperature for a given perturbation of planetary heat balance, but an enhanced regional and seasonal environmental response due to non-uniformity in poleward heat flux, and to the energy relationships of phase change and albedo change connected with ice and snow cover. The environmental response of the Arctic is characteristically different from that of the Antarctic because of differences in planetary geography and energy circulation. Ecosystems that have adapted to the low natural energy flows of high latitudes are relatively more sensitive to a given change in magnitude and timing of available energy, and to changes in physical and geochemical conditions, than most of those in lower latitudes. These natural sensitivities have a profound influence on human activities in polar areas. Policies to adapt to, or where possible to benefit from the environmental changes that will be brought about by climate change in high latitudes will have to be adapted to the distinctive environmental responses of polar areas. Careful research to understand the environmental response to climate change is essential as arctic and antarctic regions assume a greater importance in world affairs, and as the arctic regions in particular are the subject of increasing policy attention on strategic, resource development, socioeconomic and environmental protection grounds.

Introduction

The Changing Climate

Although the outer layers of planet Earth – the atmosphere and the hydrosphere – are fluids which have the capacity to transfer energy over large distances, or to store it or release it rapidly in large quantities through changes of phase, geological evidence reveals that there has been a remarkable overall stability in the physical conditions at the base of the atmosphere throughout most of the last billion years. The physical conditions at the base of the atmosphere constitute what we commonly call the climate. Within this overall stability there have been, however, changes or episodes of variation in energy distribution and surface temperature on a zonal and perhaps global basis. Some of these changes, involving alterations of mean annual regional surface temperature in excess of ten degrees Celsius, appear to have been very rapid, in terms of geological time; and at least some have been coincident with or followed by drastic changes in biological life. Within human experience, the fact that regional climate has in some cases been different in the past than it is today is a

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matter of folklore, recorded history, and the evolving pattern of human activities as society has adapted to new conditions. And within the experience of most of us and our families there is personal experience or perception that the local weather and climate has changed within a few human generations.

The possibility that human actions, related to the burning of fossil fuels and the release of radiatively selective 'greenhouse' gases from agricultural practices and industrial processes, could be a factor in causing rapid changes in global climate was noted at the end of the last century (Arrhenius, 1896), and has been discussed seriously among scientists since about 1960, when measurements of increasing CO_2 content in the global atmosphere led to calculations of the net effect on the planetary surface heat balance (Plass, 1956; Revelle and Suess, 1957). It is only since about 1977, however, that advances in climate modelling, and confirmation that the measured changes in atmospheric chemistry were indeed showing significant world-wide trends, provided convincing indications that rapid changes in global climate in the near future appeared very likely; and that human activities, if not a contributing cause, were at least having an effect that reinforced the tendency toward change. This evidence and these concerns led to the WMO/UNEP/ICSU Conference at Villach in 1985. By this time, research had progressed to the point where scientists from 29 developed and developing countries at that Conference issued the now well-known statement that:

> As a result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century, a rise of global mean temperature could occur which is greater than any in man's history. (World Meteorological Organization, 1986).

The Villach meeting stressed that our understanding of the properties, concentrations and effects of radiatively active gases in the atmosphere is now sufficiently developed that it was feasible and urgent for scientists and policy makers to begin an active collaboration to explore the effectiveness of developing a range of policies and adjustments to deal with changing emissions of greenhouse gases and adapting to the environmental changes that will result from global warming.

The Purpose of the 1987 Workshop

The 1987 workshop, held again in the delightful setting of Villach, was another important step in developing that collaboration between scientists and policy-makers. It was the task of the workshop to assess developments in scientific knowledge in this subject since the 1985 conference; and further to examine the issues affecting society that could arise as a result of future rapid global warming. Participants were asked to consider possible actions or policies that might help to 'manage' the problem of rapid climate change – that is, to bring about some significant control over the global emissions of greenhouse gases, or to adapt human activities to reduce the undesired effects of climate change. They were also to look at the knowledge needed to develop such policies, and to suggest what could be done, in a practical way, to increase that knowledge in the next few years. It was hoped that these considerations could then lead to a technical agenda that would provide a basis for discussion in the 'policy workshop' that followed, in Bellagio November 9–13, 1987 which considered questions of institutional management and implementation of policies to deal with rapid climate change.

To develop a technical agenda as a basis for policies to control and respond to rapid climate change, it is desirable to have:

- *the best information and opinion on what are the likely changes* in global climate. What are the approximate extremes of change in temperature and precipitation that might be expected? When and how rapidly might such change occur? How will different parts of the Earth be affected; and how will their environments or ecosystems respond? What will be the effect on resources useful to humans? And what is the likely effect on human behaviour and institutions?
- *a realistic view of the feasibility of controlling emissions* of greenhouse gases or their residence in the atmosphere, on a scale sufficient to have significant effect on the course of climate change;
- *an awareness of how the change in natural systems and human behaviour, as influenced by climate change, is likely to affect government and institutional policies*, and of how climate-induced policy change can affect or relate to environmental change.

This paper was delivered as the opening keynote address at the 1987 Villach workshop. It attempts to address the above requirements by sketching, in a non-technical way, a simple global climate scenario, and then considering some aspects of rapid climate change in high-latitude regions. It does not present the evidence or discuss methodologies that have led to different estimates and scenarios of what the world climate will be like in the next century. These questions were examined in technical papers given at the workshop and presented elsewhere in this volume.

Scenarios of Changing Climate

A general middle-of-the-road scenario of climate behaviour, useful for purposes of discussion of the possible policy implications of change, assumes that a few constituents in the atmosphere – mostly H_2O and CO_2 and also including CH_4 and related substances from organic decomposition and from volcanoes (whose radiatively selective gases may be counteracted or reinforced by absorbing or reflecting particulate matter, depending on the nature of the eruption) – have provided a global greenhouse warming effect for the planet over the past 600 million years or so. Because of this effect, today the Earth enjoys a mean global average surface temperature of about +15 °C, rather than a planetary surface equilibrium temperature of about −18 °C, which would be the case if the atmosphere were composed solely of nitrogen and oxygen (Bolin *et al.*, 1986). The net planetary greenhouse warming during recent geological time would therefore appear to be about 33 °C.

There is evidence that throughout geological history, there have been both short-term fluctuations (less than 100,000 years – which are almost instantaneous on the geological record –) and longer-term fluctuations of surface temperature; but these appear to have remained within about 10% of the net average planetary greenhouse warming – (i.e., ± 3 °C of a net greenhouse effect of 33 °C) (Sancetta *et al.*, 1973; Houghton, 1984).

It appears, on not very good evidence, that CO_2 fluctuations have been the principal variable bringing about past changes in greenhouse affect. Changes in concentration or 'activity' of H_2O and CH_4 appear to have been second order influences, with variable influence, sometimes acting to reinforce the change and sometimes playing a stabilizing role, depending on the biological and geological situation at the time. Some ice-core data seem to suggest that changes in CO_2 concentration have occurred very rapidly (within a few decades) in the past, and that these have been accompanied by rapid changes in local or regional climate (Dansgaard *et al.*, 1971; Larsen and Barry, 1974).

The fossil and pollen record also shows that at least some large parts of the earth have, in the past, undergone drastic rapid changes in vegetation and fauna on land, and in marine life; and that many of these changes appear to reflect or be nearly simultaneous with apparently rapid changes in regional climate (Andrews, 1972; Mathews, 1976; Macpherson, 1985).

What is the Situation Today?

Present information shows that, on a global basis, the aggregate increase in atmospheric CO_2 levels in the past century has been about 20%. The rate of increase has been about 0.5% each year for the past decade (Bolin *et al.*, 1986). The production of methane, nitrous oxides and other 'greenhouse gases' in the past is not known, but consideration of the present forms of generation of these gases suggests that releases to the atmosphere are likely to be much greater today than in the past; that they are increasing year by year; and that they are greatest in areas of industrialization and modern agriculture (i.e. in the northern mid-latitudes) (Bolle *et al.*, 1986).

The aggregate effect of these trends suggests that the heat entrapment capacity of the lower atmosphere will by the year 2030 be twice what it appears to have been in 1850. The effect of this on the climate depends upon which model one uses, and on what role H_2O has; but the middle-of-the-road scenario adopted for discussion purposes indicates that the result will most likely be a theoretical rise in mean annual surface temperature of 2–3 °C in the low and middle latitudes, and 5–12 °C in polar regions. Albedo feedback and ocean current heat transport will strongly alter the likely actual surface temperature, and in high latitudes probably increase it even more (Manabe and Stouffer, 1980; Hansen *et al.*, 1984).

High-Latitude Regions

The Physical Setting

In considering the effect of global climate change on high-latitude regions, and the interplay between high-latitude environmental or anthropogenic processes and regional climate, it is useful to review some of the characteristics of sub-polar and polar areas.

The distinctive environmental and climatic features of high-latitude areas are inter-related consequences of the geometry of the Earth, its planetary motion, and its geological history. The dominant resulting factors that are important in assessing the effects of climate change are the pattern of planetary heat flux, the presence of snow and ice, and the asymmetry of planetary geography.

(i) *The Pattern of Planetary Heat Flux*

Because of the tilt of the axis of rotation of the Earth, in high latitudes solar energy is received at a low angle, so that the net energy impinging on each square meter is much less than in the tropics. At latitudes higher than 66.7 (the Arctic and Antarctic circles) no direct energy is received at all from the sun for at least part of the year. At the same time, heat is radiated from the surface perpendicularly into space (at least from the top of the 'greenhouse' layer) from polar regions, just as it is from every other part of the planet. Nevertheless there is, somewhat surprisingly, a near balance in annual radiation budget at the surface over almost all of the arctic (Barry and Hare, 1975), but a strong year-round atmospheric cooling by long-wave radiation from the tops of clouds and moist layers.

As a result, there is a strong net loss of energy from high latitudes. This loss must be made up by transport of heat from low latitudes through ocean current and atmospheric circulation (The Polar Group, 1980; Aagaard, 1982).

These factors make the regional climate of polar areas very dependent on

(a) meridional transport of heat from low latitudes;

(b) the heat-trapping effect of clouds and greenhouse gas.

Changes in global energy balance or circulations which have an effect on these mechanisms of heat delivery or heat loss (Von der Haar and Oort, 1973; Oort, 1975), can thus have an exaggerated effect on the climate and environment of high latitude regions.

(ii) *Snow and Ice*

The thermal conditions in high latitude regions are such that, over extensive regions, totalling about 10% of the planet's surface, the average surface temperature is below the freezing point of water. This means that water substance on the land or ocean surface, in the air and in the ground, is commonly in solid rather than liquid state (snow and ice in its various forms). The effects of this familiar phenomenon are many, but among the most important from the standpoint of climate change are:

- the cover of snow on land and ice-covered sea greatly *increases the regional albedo* or reflectivity. The radiant energy received on the surface, already less than in other parts of the planet because of low solar inclination, is efficiently reflected, still further reducing the amount of energy absorbed by the ground or the ocean;
- *most of the energy gained or lost at the surface is tied up with change of phase* – melting or freezing or sublimation – rather than contributing to change of temperature. There is thus an enormous 'temperature lag' compared to changes in energy transfer in lower latitudes; and this has important implications for hydrological, chemical, and biological processes;
- *the low-level clouds are composed of ice crystals*, rather than water droplets as in most regions of the world. This condition alters the ability of clouds to absorb and transport chemical pollutants and particulate matter, and also changes the characteristics of clouds in high latitudes for transmission and reflection of energy of different wavelengths. The net results of these phenomena are not fully understood, but they include selective transport of chemicals over long distances, and differential build-up of short wave energy near the surface and loss of long-wave radiation (Weller *et al*., 1975).

(iii) *Planetary Geography*

The geological architecture of the Earth is such that the north polar and south polar regions are very different. The arctic regions, as is well known, comprise large continental land masses surrounding a small central ocean that has restricted communication with the world ocean system; while the antarctic regions consist of a high central continent surrounded by a broad ocean that is integral with the major world oceans. The result is a distinctly different planetary and regional energy distribution system in the Arctic from that of the Antarctic, and an asymmetric response to perturbations in climate.

Estimates of the proportion of total heat flux to the Arctic that is delivered by the ocean compared to the atmosphere vary considerably (Timofeyev, 1962; Aagaard and Greisman, 1975; Barry and Hare, 1975; Aagaard *et al*., 1979), but the energy delivered by the ocean is significant, perhaps dominant. It is delivered through one major point of entry, the northeast Atlantic, and it may keep the surface from freezing as far north as Lat. 82° N. (Aagaard, 1982). Heat is delivered to arctic regions through atmospheric transport by excursions of mainly zonal flow which pick up energy from warmed ocean and land surfaces in mid-latitudes and carry it quickly but irregularly and in relatively small quantities to various parts of the northern circumpolar regions (Maxwell, 1980). The short-term regional arctic climate is thus sensitive to relatively small perturbations in the strength and patterns of the North Atlantic and North Pacific Ocean currents, and to the north-south fluctuations of the boundaries between polar and temperate air masses (Roots, 1982).

The Antarctic, on the other hand, experiences a vigorous zonal circulation in both ocean and atmosphere, and its large ice-covered continent produces a relatively stable polar vortex that acts as a 'heat sink' and effectively anchors the pattern of southern hemisphere climate fluctuation (Serlapov, 1969; Newton, 1972; Price, 1975).

Climate Change and the High-Latitude Environment

The ice cover on the Arctic Ocean affects the regional climate in two important ways:

(1) It drastically changes the albedo of the northern regions, reducing the absorption of solar energy;

(2) It provides an insulating blanket (aided by the snow on the surface) that restricts heat loss from the ocean and exchange of water vapour and gases between the ocean and the atmosphere. The result is a relatively stable, stratified ocean, with a distinctive low-saline mixed layer. Heat loss through sea ice is two to four orders of magnitude less than from the open ocean. If a sea ice cover is cracked, so that only 1% is open water or 'leads', more than half the heat loss and moisture exchange will be through those cracks (Holmgren and Weller, 1974; Untersteiner, 1982).

These phenomena have great importance for the formation and location of stratus clouds, and thus for regional heat and moisture transfer; but they are very difficult to model on a regional scale.

In the last decade, the area covered by sea ice in the northern hemisphere, as observed by satellite, has varied from a maximum of about 15×10^6 km^2 to a minimum of about 5×10^6 km^2. The distribution of ice of various thicknesses and ages is much less easily determined, but a careful analysis by Vowinkel and Orvig (1970) of all reliable observations to that time indicated that about 61% of the Arctic Ocean was covered with ice five years or more old, with a mean thickness of about three metres. Dramatic year-to-year and decade-to-decade fluctuations in the extent and nature of sea ice, as for example the expansions in 1938, 1968, 1981, seem to be associated not with identifiable changes in arctic temperatures or atmospheric pressure fields but perhaps to changes in the Pacific and Atlantic low latitudes that affect the oceanic and atmospheric heat transport and the circulatory current strength in the Arctic (Lamb, 1982). A mariner's rule of thumb, not confirmed or disproved by regional observations, is that years when the sea ice extends farther to the south than 'normal' are rarely years of severe climate conditions in the arctic itself, but tend to be years when the denseness and severity of ice in the Arctic Ocean are reduced.

With the degree of climate warming predicted over the next century, it appears reasonable to speculate that the Arctic Ocean ice cover could disappear. The change in net albedo, the increased source of atmospheric moisture from an ice-free ocean, the consequent increase in cloudiness and precipitation would dramatically change the environment of arctic continental regions, many parts of which at present get little precipitation and are technically deserts. Obviously the physical, probably the chemical, and certainly the biological conditions of arctic marine areas would also be profoundly different if the ocean were free from ice. Regional climatic models have not yet been able to examine the resultant environmental changes; but there are some crude analogues from Pleistocene interglacial periods, when temperatures were 4 to 12 °C higher, sea ice appears to have been absent or local, rainfall in northern regions apparently much greater, and forests extended to the present Arctic Ocean coasts in North America and Siberia (Mathews, 1967; Blake, 1972; Clark, 1982).

In the Antarctic, by contrast, the same amount of global warming would increase snowfall on the continent and surrounding ocean, leading to increased glacial activity, likely expansion at first and then thinning of the marginal ice shelves, increased discharge of icebergs, and most probably an intensification of the Antarctic Convergence, the narrow zone of contact between the cooled Antarctic marine waters and the upper layers of the world ocean system (Polar Research Board, 1983; Budd and Smith, 1985; Meier *et al.*, 1985). If the warming occurred rapidly, the first effects would appear to be intensified storminess and increased precipitation rather than marked change of surface temperature; and increased vigor of the icecap and glaciers as they thickened, with instability of parts of the Antarctic ice sheet and ice shelf margin as the fringing ice shelves thinned and lifted off their anchoring shoals (Weertman, 1974). The longer-term consequences of even a short-term warming could well be a tendency toward massive episodic surges of portions of the Antarctic icecap, possible drastic changes in the West Antarctic Ice Sheet, with consequent effects on sea level, and on the pattern and intensity of formation of Antarctic bottom water, which in turn influences the three-dimensional circulation of the world ocean (Kuhn, 1981; Jezek and Bentley, 1984; Jacobs, 1985). The climatic effect of the changes in antarctic sea ice cover which would result from changes in surface temperature have not yet been carefully modelled on a regional basis, but from global modelling considerations it appears reasonable to expect that a significant reduction in the area covered by sea ice would lead to a reduction in the instabilities that at present result from large annual variations in southern high-latitude albedo and heat transfer (Zwally *et al.*, 1983).

The marked asymmetry in response of north polar and south polar regions to climate warming on a global scale has parallels in northern regions themselves, which exhibit many regional or local variations in environment and productivity under present climatic conditions. Some of these variations would be exaggerated, others lessened, under a climate which had undergone rapid warming (Roots, 1982; French, 1986).

High-latitude Ecosystems

The biological systems that have evolved in or adapted to high latitude regions are by necessity low-energy systems, able to cope with strong seasonal changes in energy flow and physical conditions. Survival within a low-energy unstable ecosystem has been achieved through evolution of a variety of energy-conserving life forms and behavioural patterns (Dunbar, 1979). Some plants or animals develop shapes and structures that reduce heat loss or serve to absorb maximum energy from the environment; others have evolved life cycle systems that can be interrupted or spread over an extended time, such as plants that may take several years to progress from flower bud to seed (Wielgolaski, 1987), or muskoxen which may not breed during poor years until, apparently, the herd accumulates enough collective energy to reproduce (Gunn *et al.*, 1984). Other species, like whales, caribou and many birds, have developed nomadic or migratory habits, collecting dispersed biological energy from a large area (Cooch *et al.*, 1987). All of these adaptations, and those of their competitors, predators, and parasites, have become specialized to cope with the distinctive environmental conditions imposed by a polar or sub-polar climate (Dunbar, 1982). When the climate changes, these specializations may put the organism or the population at a disadvantage. In some cases, of course, the change of climate could open up new habitat which some already specialized or adaptable organisms may exploit to advantage.

The net result of high-latitude environmental conditions is that the ecosystems in those regions tend to be highly specialized, immature in the sense that there appear to be unfilled ecological niches, and characterized by considerable energy and nutrient losses or storage at the interfaces between trophic levels. Food chains on land and in the sea are commonly short and simple compared with those of lower latitudes, and the species and populations at higher trophic levels are sensitively dependent on the welfare of a few species or even a single population at lower levels. The biological communities are typically stressed and limited more by physical factors than by biological competition. Such ecosystems tend to be sensitive to physical disturbance, by natural or human causes. Wide swings of numbers, from local extinction to rapid expansion to very large numbers of temporarily favoured species or populations, are typical of northern ecosystems (Bliss, 1981; Roots, 1987). Whether the same is true of antarctic ecosystems is not yet clear; but on the whole the southern polar and sub-polar systems appear to be somewhat more stable (Knox and Lowry, 1977).

Marine ecological conditions in high latitudes are on the whole more stable than those on land; but they are nevertheless subject to environmental variations more sudden and violent than those in lower latitudes. The presence or absence of cracks or shore leads in the ice-covered ocean, and year-to-year fluctuations in the area covered by sea ice or the amount of snow on the ice, have drastic effects on light penetration into ocean waters, and on heat and gas exchange with the atmosphere. Thus, in high latitude seas and oceans, primary productivity, which is already low, may vary widely from place to place and from year to year or decade to decade, depending upon the vagaries of the weather and short-term fluctuations in the atmospheric and oceanographic climate. Changes in primary productivity produce consequent fluctuations in the distribution and populations of higher organisms (Golikov and Averincev, 1977; Hempel, 1985; Baker and Angel, 1987).

Although direct comparisons are impossible to make, there seems to be good evidence that the low-energy high-latitude terrestrial and marine ecosystems are more vulnerable to dramatic disturbance by rapid changes in climate (depth and duration of snowfall, ambient temperature determining the length of the growing season, variations in gas content in the oceans, etc.) than typical ecosystems at lower latitudes. The rate of change, rather that the absolute amount or extent of change, would appear to be a particularly critical factor in the ability of high-latitude ecosystems to adjust to new conditions. There is simply not enough surplus biological energy in the system to enable organisms or communities to make rapid changes in behaviour or physiology. Some key species, like the Antarctic krill, are already paradoxically high users of energy (Kils, 1983) and may be particularly vulnerable to climate change which would change metabolic conditions; and a moderate change in such key species could have severe effects on the ecosystem. At the same time, high-latitude biosystems are tough, and aided by the absence of competitors, a few survivors can repopulate a whole region, whereas in other parts of the world, recovery from catastrophic die-off may be very difficult or impossible. In the most extreme polar conditions, such as those to which the endolithic vegetation and some of the lichens and arachnidae of inland Antarctica have become adapted (Friedman and Kibler, 1980), the vulnerability of organisms to climate change may well be less than those of more 'typical' northern or southern ecosystems; but such areas are probably of little importance in the global biological picture.

Climate Change and Human Activities in Northern Regions

Of particular importance from the point of view of human uses of the Arctic is the great heterogeneity of northern biological conditions and the vulnerability to disturbance of the most productive habitats. In all northern areas, both terrestrial and marine, there are restricted or localized areas that are biologically more productive than the surrounding regions in the same general environmental setting (Roots, 1979; Thomas and MacDonald, 1987). These "northern oases" are centres of recruitment and dispersal for the northern biosystems; and many have naturally become the centres of human settlement and exploitation of living resources. The reasons for the anomalous fertility or productivity of these areas are varied, usually complex, and in most cases not clearly understood; but in most instances appear to involve a delicate interaction of local conditions of temperature, precipitation, and photosynthetic energy and topography, available nutrients and air or water current patterns in a restricted area (Bliss, L. C., 1977; Webber, 1978). Many of the most productive areas, or oases, appear to be unstable, and have been transient even within historic time. Such phenomena are especially vulnerable to small changes in climate; but which way they will be altered by what changes in what climate parameters is difficult to determine, and cannot be predicted through modelling studies of average or general regional changes.

The human activities in northern regions have, like the natural ecosystems, become specialized to adapt to the mixture of environmental conditions determined by the present northern climate. Both the indigenous cultures that have developed around the polar basin since pre-historical time, and modern industrialized activities in the north that have become established in the past three decades have developed distinctive technologies and life styles to cope with the mixtures of snow and ice, low temperatures and short annual growing seasons characteristic of northern regions. Changes in northern environmental conditions, resulting from changes in northern climates, therefore will require changes in the cultural response, technology, investment and activities of northern peoples.

Modern technological penetration into the arctic regions, connected with industrial development of petroleum and mineral resources, military operations, or transport and communication services, while not dependent directly on the distribution of biological resources, is nevertheless also subject to conditions of the northern environment and climate change. Although some modern towns in the North are the direct outgrowth of earlier settlements that were dependent on hunting or fishing and thus are in biologically favourable locations, and others are dependent on the geological accident of a mineral deposit, most modern habitations in high latitudes are at sites connected with transportation – harbours, conditions suitable for airports, nodes in overland or river transport, etc. The characteristics which make these local places particularly good as sites for settlement are in many cases the very characteristics that will be most vulnerable to alteration by changes in climate, through resultant changes in sea ice, permafrost or river flow, or weather conditions (French, 1986).

In the modern context, as policies of all kinds in northern areas have developed in response to prevailing environmental conditions, a change in environmental conditions caused by a change in climate will necessitate a change in policies. Because in most northern countries, slight changes in climate often result in rather dramatic changes in environmental conditions that are important to human activities, policies and the success of the policies can be very sensitive to slight changes in climate. This is true on a variety of time and space scales, from municipal to international (Roots, 1986).

Practical Decisions Sensitive to Knowledge of Climate Change

A few examples from Canada illustrate the sensitivity of policies and management decisions in northern countries to changes in northern climates:

(1) The annual budget for removal of snow from the streets of the metropolitan

area of Montreal (population 1986 approx. 2.9 million, mean annual snowfall 1960–1976 approx. 2.5 m) is enormous. By some accounting, it is about the same as the annual operating budget for the public portion of primary education. Thus Montreal area city administration and taxation authorities have a major planning and expense concern that is not present in a city of comparable size where winter snowfall is not an important factor. The annual snowfall may vary from one year to the next by 50% or more. The expenditures for snow clearing, however, may vary by a much greater amount; for unusual or repeated blizzards, which seem perversely to occur on weekends necessitating overtime or emergency payments, etc., may double or triple the average operating budget, even though the physical amount of snow removed may not be unusual. A small change in climate, causing a change in timing and amount of snowfall, can have severe policy implications for a city like Montreal, affecting, inevitably, the ability to meet all other expenses such as those for primary education. At the present state of the art of predicting local snowfall, the city fathers cannot depend on the meteorologists and climatologists to make adjustments in advance to their annual city winter financial budget. They thus must work on averages based on past experience. It is not politically popular in a tax-conscious city to tie up money in equipment and manpower waiting for snow that does not come; but it is political suicide for any city government in Canada to be caught with a heavy snowfall and have neither the equipment nor the money to remove the snow promptly. A change of climate, expressed as a change in the "snowiness" of winters or an increased or decreased frequency of extreme events, becomes for Montreal a local political issue.

(2) An important factor in the Canadian economy is the ability to grow large quantities of wheat near the northern limit of the range of cereal grains, where strong summer sunlight and daily variations of cool temperatures produce a starch in the wheat seed that brings premium prices on world markets. But growing wheat at the northern limit of its range is a risky business. Most of the risks are related to variations of weather and climate. Canada has developed many policies to encourage wheat-growing in the northern prairies and to help reduce the risks both to individual farmers and to the national and international wheat investment market, which buys and sells the wheat even before it is planted. Thus both farmers and financiers gamble on the anticipated climate. National grain policies are inevitably climate-related, and sensitive to variations in climate, and they affect many aspects of the grain growing and marketing business, from crop insurance, the value of land and of shares in the farm machinery manufacturers, to the national balance of payments and interest rates.

Under present conditions, a 1 °C increase in average annual temperature in the northern Canadian prairies would move the northern limit for No. 1 hard white premium wheat north by about 100 km, provided moisture patterns stayed the same. But a 3 °C rise would most probably increase the likelihood of widespread drought during the critical period of late spring and early summer, and later in the season the increased evapotranspiration would likely lead to a decrease rather than an increase of total wheat yield from the entire region. Thus agricultural policies on the northern prairies are exceedingly sensitive to the nature and severity of changes in climate, on an annual and decade-long basis. Ability to forecast the effect of temperature change on precipitation distribution and moisture balance becomes of the utmost importance.

(3) The dominant factor spurring development of arctic Canada and Alaska during the past twenty years has been the possibility of exploiting the petroleum deposits that lie along the coasts of the Arctic Ocean. Many billions of dollars have already been spent in exploration, development of specialized technologies, in building the infrastructure that is necessary to carry out major modern industrial operations in a region that because of a harsh climate has been sparsely populated and little developed; and in protecting the environment and the rights of the small numbers of people who already live there. All of these expenditures have been related to or based on the climate conditions of the past two decades.

The petroleum industry and energy authorities are now at the stage where, in a time when world petroleum prices are low and world interest rates are high, difficult decisions must be made about the further exploration and exploitation of northern petroleum deposits. Substantial deposits of natural gas, and a considerable amount of oil have been discovered and there is geological promise of more. Technology is available to develop the deposits and deliver the products to market, but only with heavy investment many years before market sales could bring a net profit. The decisions are directly affected by the risk of climate change and the ability to predict it. For example, if large deposits of oil are confirmed in the Canadian Arctic, should the oil be brought out by tanker, and have access to world markets, or by a 4000-km long large-diameter pipeline and be tied to a regional North American market? How do the comparative differences in cost of the two modes of delivery relate to different factors of dependability, or of risk of environmental damage from accidents or routine operations? All of these questions have an important climatic component. Should icebreaking tankers be designed for present ice conditions, knowing that at least on paper they will have to be amortized over a 30-year period, but that sea ice conditions will almost certainly change within the next 30 years? If icebreaking tankers and the supporting system are built, and in a few years the ice becomes much lighter, the companies and the government will be saddled with enormous investments for equipment no longer needed. If the ice were to become still heavier or icebergs increase dramatically, the equipment will be inadequate and the whole shipping operation might become impractical unless it moved into a new dimension, such as submarine transport, which would open new problems, new technologies and quite new costs – perhaps also new market structures and new markets. Different but equally serious dilemmas are found on land: – either a warming or a cooling of climate, over a period of decades, would change the conditions on the upper surface of the permafrost and cause engineering or environmental problems, and therefore financial problems, for a pipeline designed for the present conditions. It appears at present that it would be prohibitively expensive to build a pipeline that would remain stable under all potential changes of ground conditions caused by conceivable changes in climate in the next 30 years.

These are examples of investment decisions and resource development policies that are very sensitive to climate change, and to the ability, *now*, to predict changes of climate in the next half century, in northern countries.

The Sensitivity of the High Latitude Environment and its Likely Response to Climate Change

Not only is the postulated temperature change in high latitudes, especially of northern regions, greater than in lower latitudes, but the proportionate environmental effect of a given climatic disturbance appears to be greater. A physiographic or biologial system that operates at low energy levels is affected by a given energy change more than one that operates at higher energy levels, if for no other reasons than that the proportional change is greater, and the processes of adaptation are slower. The same is true of human adaptation and technology. When, as in the northern regions today, the ambient temperatures fluctuate above and below 0 °C and the environmental processes are dominated by the distinctly different behaviour of ice from that of water in marine, terrestrial and biological systems, it is evident that slight changes of global surface temperature can have exaggerated effects on environmental conditions and on northern living systems. The changes in climate can have both immediate and long-term effects on human activities, the technologies used, and their costs. In the examples given above, climate variations affect policies and decisions on a range of time scales: a city government must respond to snowfall in a few hours; agricultural policies must provide for decisions at least one year in advance; pipeline or shipping design and investment should take into account changes in several decades of climate extremes.

The response of different aspects of the northern environment and ecosystems to small changes in climate varies greatly in geographical scale and in rate. Some examples of phenomena that have been studied show the range:

(i) *Permafrost*

The result of many thousands of years of sub-zero surface temperature, permanently frozen ground will respond only slowly to changes in climate, except at its southern discontinuous margins. The mass of frozen ground may remain out of equilibrium with the surface temperature for centuries or thousands of years. The upper layers of permafrost will, however, sensitively and accurately record small annual variations in mean temperature. Borehole temperatures in permafrost show convincingly that in Alaska and northwestern Canada there has been a distinct regional surface warming of 2–4 °C over the past century (Lachenbruch and Marshall, 1986). Permafrost therefore acts as a delicate recorder of climate changes, in areas where the temperature remains below freezing.

In contrast with the thermal inertness of perennially frozen ground, the 'active layer' on the surface of permafrost commonly shows dramatic annual changes, varying from place to place in scales of meters, in response to changes in climate. Changes in stability, mechanical strength, permeability and chemical behaviour of the active layer lie behind many of the engineering and environmental problems and investment headaches associated with modern industrial and municipal development in arctic regions (Péwé and Brown, 1984). Change of climate will have both short term and long-term effects on permafrost: depending on the thermo-mechanical structure of the frozen ground and the rate of warming, the permafrost may either modulate or exaggerate the surface change (Smith, 1986).

The northern areas presently underlain by permafrost most subject to change by climate warming are flat-lying, poorly drained, largely forested in Eurasia and covered with tundra vegetation in North America. An increase in thickness of the active layer in these areas would likely increase the area of wetlands. In some areas, however, increased temperatures may lead to drying of present peatlands, with consequent release of methane and thus feedback of climate-warming greenhouse gases (Chapin *et al.*, 1980; Harriss *et al.*, 1985).

(ii) *Sea Ice*

In the period of reliable historic observation (about a century), the difference in area covered by sea ice at its maximum seasonal extent has fluctuated by almost 50%, in both arctic and antarctic waters. Because the bulk of arctic sea ice is multi-year ice whose individual floes have a lifetime of several years to a decade or more, year-to-year fluctuations appear to be less erratic than in the Antarctic, where almost all of the ice is less than two years old and is more responsive to annual variations in weather and climate (WMO, 1982). In the marginal areas of the Arctic Ocean, and in the North Atlantic and North Pacific, sea ice conditions tend to display a crude cyclic pattern in which a year of exceptionally heavy ice is followed by a few years of generally heavy but less severe ice, then a couple of years of lighter ice conditions followed again by heavy ice (Lindsay, 1976, 1977, 1981). The regional and circumpolar variations in sea ice conditions are due mainly to changes in climate; but the linkage between air temperature, storms and winds, and ocean currents is not well understood, and to date it has not proved possible to predict sea ice variations in any locality or region, except in a most general way, from observed climatic data. General experience, however, would suggest that rapid climatic warming in high latitudes would produce rapid response of lighter sea ice conditions in the marginal areas of the Arctic Ocean, especially on the Siberian side, and in the Antarctic. Depending on storm patterns, cloudiness and precipitation, sea ice in the central Arctic Ocean may take a decade or more to respond; but warming of the amounts postulated would lead to instability and eventual disappearance (WMO, 1982). These changes will of course lead to profound changes in the biology of the polar oceans.

(iii) *Snow Cover, Glaciers, Icecaps and Icebergs*
Although climate models are not as yet able to identify with assurance the changes in precipitation patterns in high latitude that will come about as a result of global climate warming, there is little doubt that increases of mean annual temperature, and in particular, increases of average winter temperature will be accompanied by increased winter snowfall in the zone 50–75° North Latitude (Manabe and Stouffer, 1980). A similar but less marked change can be expected in southern polar latitudes. The result, in northern regions, can be expected to be a heavier but shorter snow season, increased winter cloudiness, increased annual runoff from low lying areas, and increased activity of glaciers in mountainous and polar regions, with gradual disappearance of those in sub-polar regions. Although most of the increased snowfall will likely be received near the coast, the Antarctic Icecap can be expected to thicken, at least for several decades; its surface gradient and velocity will likely increase, thus leading in time to expansion and greater ice discharge (Budd and Smith, 1985). The production of icebergs in both the Arctic and Antarctic will thus likely increase, and be sustained for some time.

(iv) *Sea Level Rise*
Changes in sea level due to melting of icecaps and glaciers and thermal expansion of warmed ocean waters will be worldwide and, within a year or so, simultaneous with climatic change. To some extent the delivery of water to the oceans from melting glaciers will be offset by delivery of ocean water to the polar ice sheets in increased precipitation; the timing and sign of the net water budget will depend on the rate and pattern of global warming, the size of the glacier and its regime (Oerlemans and Van der Veen, 1984; Meier, 1984; Bindschadler, 1985; Bentley, 1985). The effects of such fluctuations on high latitude coastlines will, however, likely be minor. In arctic areas, relative sea level is already mobile, because of (i) isostatic rebound after recent deglaciation, (ii) changes in ground surface due to thawing and heaving of permafrost and ground ice, especially in extensive areas of very flat coastal plains, with resulting erosion, sedimentation, build-up of organic accumulations and migration of shorelines through ice shove; and (iii) tectonic movements. On-going changes due to these causes would likely mask any effects due directly to sea level rise caused by global climate change. But in areas where isostatic rebound is not active and where thawing of ground ice is already leading to widespread relative lowering of ground surface, as along parts of the coast of the Beaufort Sea, climate-induced sea level rise may increase coastal erosion, and influence inshore marine sedimentation.

In the Antarctic, most of the continental coastline is floating ice, and changes in sea level area of no consequence, except to cause a small landward displacement of the tidal hinge line. The limited coastal areas that are ice-free and the rocky sub-antarctic islands all have steep coasts, unaffected by small changes in mean sea level. There are numerous places where a half metre or less of sea level change could have local biological significance by making it easier, or harder, for penguins and seals to go ashore; but the net effect would probably be negligible.

In contrast to some other parts of the world, relatively few people have permanent habitation or make their livelihood within one meter of sea level in the Arctic, and none in the Antarctic. The social effect of sea level rise due to climate change is not an important factor in high latitudes. Industrial facilities built at the shoreline or offshore will have to cope with changed water depth and changed hydrological and ice conditions, especially in estuaries and deltas; but such problems would appear less than in lower latitudes. On the other hand, major changes in the Greenland and Antarctic Icecaps and smaller sub-polar glaciers due to climate change can be an important contributer to world-wide changes in sea level, with socioeconomic consequences in other regions (Oerlemans, 1989).

(v) *Boreal Forest*

Geological evidence suggests that the boreal treeline is relatively opportunistic with respect to climate change (Nichols, 1975; Ritchie and Hare, 1971). Pioneer species can advance into new territories quite rapidly – tens of kilometres per decade if suitable new habitats open up –, while mature trees show remarkable ability to survive, even if they cannot reproduce, when conditions change in an unfavourable direction (Kay, 1978; Singh and Powell, 1986). Throughout most of the boreal region, the vigour of the forest ecosystem appears to be controlled more by availability of nutrients and energy for photosynthesis than by temperature, and so the sensitivity of the forest to climatic warming is likely to depend upon associated effects on precipitation, cloudiness, and chemical weathering perhaps even more than on the increased temperatures themselves (Kauppi and Posch, 1985; Davis and Botkin, 1985; Pennington, 1986).

(vi) *Colonization of the Tundra and Arctic Desert*

Recent studies have provided information on the migration of flowering plants and some shrubs into the tundra and high arctic desert during the past few centuries (Edlund, 1986). As with the boreal forest, the limiting factors for viable plant communities in the high Arctic appear to be not severity of temperature but availability of nutrients and water. Climatic warming may thus be expected to have an effect on arctic vegetation (and thus on the animal life dependent on that vegetation) according to its effect on soil moisture and nutrients, especially nitrates. Little is known about the ability of soil bacteria and other micro-organisms to migrate in the tundra and populate the arctic desert if conditions change; but tundra vegetation, of which there is a high proportion of biomass beneath the ground, appears to be less dependent on organic preparation of suitable soils or the presence of specialized bacteria or mycorrhiza than do the more productive vegetation systems in middle latitudes (Svoboda and Henry, 1987). Terrestrial animal life can be expected to vary considerably in its ability to respond to rapid climate warming in the arctic. Many invertebrates can migrate immediately to wherever the habitat is suitable; but others, such as wingless insects, worms, and spiders, may respond slowly and erractically. Most vertebrates will of course move as rapidly as the vegetation upon which they directly or indirectly depend (Harington, 1986).

(vii) *Aquatic and Marine Habitats*
From the limited evidence available, it appears that the main changes in high-latitude aquatic and marine habitats directly attributable to climatic warming will be caused by the physical responses: e.g., increased spring and summer stream run-off, lessening of the thickness and duration of ice cover on lakes, rivers and the coastal ocean, and increased temperature of the surface water layers in summer. These changes will undoubtedly affect aquatic and marine productivity and the composition of the biological communities. The species composition of northern aquatic and marine ecosystems appears to be quite dynamic: perhaps more so than ecosystems in warmer waters (Oliver, 1964; Johnson, 1976; McCart and Den Beste, 1979). Important elements of the arctic (and also antarctic) marine ecosystems are dependent on the location and intensity of the brief summer 'algal bloom'; yet the geographical position of the bloom, determined in part by the position of the sea ice margin, may vary tens or hundreds of kilometres from year to year (Smith and Nelson, 1985). The structure of northern biological communities may change within decades. Two examples of documented changes in the past century are the change in species mix of major fish in Ungava Bay since the International Polar Year 1882–83 (Dunbar, 1983); and the growth, then decline, of the West Greenland salmon fishery in the middle years of the present century (Dunbar and Thomson, 1979). Both of these changes appear to be due to natural causes, related to the minor climate changes that have taken place during this period. They may be an indication of the sensitivity of high latitude marine ecosystems to climate change, and of the kind of dramatic biological changes that might be expected in the event of warming of the high-latitude environment.

Climate Change and Human Response in High Latitudes

Several studies (Kellogg, 1981; Flohn, 1981; Siedel and Keys, 1983; Schelling, 1984; WMO, 1986; French, 1986) have considered what might be done, by means of deliberate human policies and their subsequent implementation, to avoid, mitigate or cope with the anticipated but undesired effects of climate change. These studies cover a wide range of actions and their possible consequences in different parts of the world. One common feature of these investigations and speculations, however, is an indication or implication that, except for political problems that may be caused by geographic shifts of activities across political boundaries, most postulated changes in climate could have neutral or even advantageous consequences for human society and economy if the changes occur gradually. However, the same studies point out or imply that almost all of the foreseen effects of very rapid climate change appear to be deleterious or negative. Therefore, it is not just the magnitude and distribution of climate changes expected, but even more critically the rate and pattern of change, that determines the options open to society to affect the course of change or to adapt successfully to new environmental conditions.

The actions that might be taken may be grouped into four main categories. It could, in principle, be possible:

(i) to exert some control on the changes in climate by influencing the causes of change, i.e., by controlling the production or release of greenhouse gases, CO_2 and CH_4;

(ii) to influence the change in climate by affecting the natural feedback mechanisms that determine the net balance of greenhouse gases in the global atmosphere;

(iii) to modify the natural system to facilitate or help direct the environmental response to climate change, and thus to conteract the undesired effects or take advantage of the changes that occur;

(iv) to adapt human activities to rapid climate change and to the new environmental conditions that will come about as a result of changes.

A brief summary, for discussion purposes, of how policies in these four areas might apply to high latitudes (Roots, 1986) suggests the following:

(i) *Controlling at Source*

It would be possible, through resolute applications of international policies on energy use and industrial development, to curtail the burning of fossil fuels and so slow down the current increase in production of CO_2, and to modify agricultural practices to reduce the release of methane to the atmosphere. The practical and economic difficulties of implementing such changes on a scale that will have a significant effect on global atmospheric trends would be of course enormous. Regardless of the feasibility of such policies and actions, they would not apply in any significant way to high latitudes. Despite the high per capita energy consumption in arctic and antarctic regions, the amount of industrial and agricultural activity and the total human population is so small that the contribution of high latitudes to total planetary production of greenhouse gases is, and is likely to remain, insignificant. On the other hand, rigid application of world-wide policies to curtail the use of fossil fuels might have a comparatively more crippling effect on the economic and social development of high-latitude regions than in many other parts of the world.

(ii) *Affecting Natural Feedback Process*

Northern forests, peat-bogs and muskeg contain a significant portion of the stored non-fossil carbon on the planet, and action to maintain that storage and reduce the rate of carbon oxidation or hydration could affect the global carbon cycle and the concentration of carbon-based greenhouse gases. Because of the very large areas covered by boreal forests and wetlands, policies to increase carbon storage might conceivably have global significance. As trees in the boreal forests have a very long re-cycling time and thus are at an economic disadvantage for wood production compared to lower latitudes, and as much of the northern forest is marginal or unsuitable for agriculture, it may be worthwhile to look carefully at the feasibility of developing boreal forest lands not for timber or fibre production, but to increase the store of sequestered carbon on a global basis. The relatively greater increase of temperature expected in boreal regions compared to lower latitudes could favor rapid increase in the carbon-fixing capacity of the northern margin of the forest. Increases of CO_2 at ground level will also have some effect in favouring plant growth. There is also scope for planning the more intelligent management of the distinctive 'urban heat islands' that develop over northern settlements in protected locations, to use their characteristics to ameliorate local discomfort and at the same time contribute to the reduction of greenhouse gases (Benson and Bowling, 1975).

Northern wetlands are not only a deposit of carbon of considerable magnitude. Depending on the height of the local water table and conditions at the surface, they may act either as a source or a 'sink' for methane (CH_4) over extensive areas (Harriss *et al.*, 1985). It may be that relatively simple engineered modifications to the drainage of large northern muskegs could be a more economical and effective way of controlling increases of CH_4 release than changes in agricultural practices. Warmer temperatures will of course increase plant growth and carbon fixation in wetlands; the management problem will be to reduce carbon release. Schemes to fix carbon over large areas may at first appear quite impractical at the present time; however, their feasibility, and the possibility of developing the international incentives needed to bring them about should be explored.

(iii) *Modifying the Environmental Response*

There are a number of things that could be done, through policies or actions distinctive to the high-latitude regions, to alter the local or regional response to rapid climate change in order to take advantage of the changes that may be expected, or to reduce the undesired local consequences. Examples might include:

- stabilisation, insulation, or drainage of permafrost. Permafrost management is developing rapidly as an applied science. Various techniques, and both synthetic and natural materials, are applied successfully today to keep the upper surface of permafrost in a frozen state, or to enhance its thawing, as desired (Péwé and Brown, 1984). This knowledge and experience could perhaps usefully be applied to the problems of climate change in regions presently underlain by permafrost, in advance of the effects of the changes themselves, in order to reduce undesired consequences and where desired, to take advantage of climate warming in ways that are planned and controlled.
- change the albedo of snow and ice. The reflective properties of the snow surface have been changed deliberately over local areas to accelerate thawing. The same process takes place inadvertantly over larger areas as a result of dust from highways, industrial pollution, etc. Schemes have been proposed to melt the arctic sea ice by this technique. Most studies to date appear to suggest that, under present conditions, the energy and logistics reequirements for large-scale appli-

cation of these techniques would be enormous; and that the broader environmental consequences of accelerated melting of snow and ice would outweigh the expected benefits. But in the event of accelerated climatic warming, when the pattern of movement, stream break-up, and sea ice disintegration can, in any case, be expected to be considerably different from the present, deliberate management of thaw and break-up through artificial control of surface albedo may deserve consideration.

- clearance of channels in sea and river ice. Techniques are well developed for control of river break-up by cutting channels in the ice to relieve ice pressure and direct ice movement so as to reduce damage to shorelines and man-made structures. These techniques have also been effectively used at sea to avoid damage to vessels and offshore structures. Although such actions are local, the effect of a few well placed channels can be very widespread. It can be expected that during rapid climate warming and likely deterioration of ice cover, such techniques will be even more effective and widely used.
- iceberg management. A wide variety of techniques is used today to deal with icebergs that threaten offshore fixed structures and shipping lanes. These include burying installations beneath the sea floor; construction of fixed berms that will stop or deflect all bergs with draft greater than the top of the berm; towing or pushing icebergs away from impending collisions with structures; and disintegration by explosives. Most scenarios of climate warming predict an increase in the discharge of icebergs into the Northern Atlantic, and possibly into parts of the Gulf of Alaska. The increase would likely be sustained at least for several decades, and be accompanied by a parallel increase in discharge of ice from the antarctic icecaps into the Southern Ocean. It can be expected that increased attention and resources devoted to iceberg surveillance and management will be one of the international actions taken early as a consequence of climate warming.

  There is another side to the matter of increased icebergs. If the warming of the climate is accompanied by increased aridity and water shortage in lower latitudes, the arctic and antarctic icebergs may acquire a new value as a fresh-water resource, and iceberg management may include problems of the collection and dependable delivery of this resource.
- diversion or re-direction of rivers. During the past century, proposal to harness or divert the rivers that flow north into the Arctic Ocean, in order to bring this water or their power to more populated and potentially productive regions have been put forth repeatedly in both North America and Eurasia. None of the proposals has progressed beyond the initial planning states, because the economic and environmental obstacles have appeared to be too great. The Soviet Union recently enacted legislation formally cancelling the former programs of study and planning for diversion of water from rivers presently flowing into the Arctic Ocean (U.S.S.R., 1986). In the event of a rapid warming of climate, however, some of the proposals may have to be assessed in a different light. The apparent

need or market for northern water will be altered by changes in temperature, precipitation, and hydrological systems in middle latitudes. The hydrology of the northern rivers themselves, and the assurance of adequate supply, will likely be altered considerably. There will also be changes in the intervening drainage systems through which the waters would have to flow to reach markets in the U.S. or southern U.S.S.R. Such changes will affect the engineering feasibility and cost of major diversion schemes. Environmental consequences also will be changed. The change in Arctic Ocean ice conditions and in sea level could influence the environmental and industrial consequences of reducing the flow of water to the ocean. Any proposals for management of large northern rivers must take the likelihood of future climate change into account; and evaluation of the proposals is dependent on a prediction or assessment of the characteristics of climate change and its environmental consequences.

- creation of deliberate heat islands. Except in the most windy locations, all large arctic towns and industrial installations at inland locations are surrounded, most of the time in the winter, by an 'urban heat island' where the low level air temperature is warmer and humidity higher than in the nearby countryside. Water vapor and particulate matter from exhausts and chimneys create a semistable airborne blanket of polluted ice crystals that changes the local radiation and heat transfer balance and creates a local "greenhouse" effect. Although the city temperatures are consequently less severe than those in the surrounding countryside, an arctic heat island brings problems of pollution, fog, and discomfort (Benson and Bowling, 1975). A similar phenomenon, although less marked and less stable, sometimes develops over large cities in mid-latitudes during cold weather (Hare and Thomas, 1974, Chapter 12). Techniques for deliberate creating of small heat islands are used in lower latitudes to prevent frost damage to fruit trees. A warming climate would probably lead to conditions where these techniques could effectively encourage farmers to grow crops farther north than at present, and lead to conditions where the need for and practice of frost damage control is widespread. Although the frequency of dramatic inadvertent and undesired heat islands over arctic towns, with their attendant problems of local pollution and poor visibility, will likely be lessened, warmer conditions in northern latitudes may offer increased opportunities for meso-scale climate control.

(iv) *Adapting Human Activities to Rapid Climate Change and New Environmental Conditions*

Throughout history, people have adapted or adjusted to change in environmental conditions by one or several of four main types of actions. They may (a) store food, fuel, etc. that is surplus from more productive periods, to be drawn on during 'lean' times; (b) they may set up systems of insurance, compensation, or aid so that the damages are distributed through society and those most adversely affected are helped by those less affected; (c) they may employ different techniques or behavioural patterns more suited to the new conditions; and (d) they may migrate to new areas where living conditions are perceived to be better. The first two of these strategies, to be effective, require some foreknowledge or premonition of impending change, and can provide only temporary help or solutions: they are undertaken in the expectation that the changed conditions are a deviation from a 'norm', to be followed by a return to "normal" conditions. Only the other two categories – change in technology or human behaviour, or migration to new localities –, can be effective adaptations to the long-lasting different environmental conditions that might be expected from global increase in greenhouse gases. It is interesting to speculate on what some longer-term adaptive changes might be with respect to high latitude regions in anticipation of, or response to, the climate changes postulated.

Rational adaptation to new conditions will have to take into account the putting into use, in polar and boreal areas, of practices and technologies that were previously typical of warmer areas in lower latitudes, as well as (or modified by) technologies and practices distinctive to the arctic and antarctic regions under new conditions. If the change of climate is gradual enough so that severe ecological disruption is avoided, the warming of sub-arctic regions could be expected to lead to an increase in human population, greater industrial development, and more widespread farming particularly in Alaska and Siberia where there are extensive areas of suitable soils and terrain, to take advantage of more vigorous growing conditions. Forest industries will, after several decades, likely move northward throughout the entire circumpolar region as larger trees grow at higher latitudes. If on the other hand the warming is too rapid for natural systems to adjust in a fashion that maintains overall productivity, careful human management will be necessary to take advantage of the more favourable conditions, and to prevent severe problems of erosion, flooding, loss of soil fertility, outbreaks of disease and parasites, etc. which are frequent symptoms of disordered environments.

The successful accomplishment of these changes will require recognition by national and local governments of the nature of the response of the northern environment to climate warming, and research and planning on many fronts (McKay and Baker, 1986). Areas needing attention will include: development of varieties of crops suited to changed conditions; policies and programmes to preserve genetic diversity in an increasingly unbalanced and human-managed landscape; environmentally sensitive and imaginative town planning and development of major transportation networks; and perhaps most important, new methods for financing the advance investment needed to prevent the social and economic disruption that could otherwise be the result of environmental dislocations in the high latitudes – those parts of the planet which will undergo the greatest change in the event of global climate warming.

Critical Issues and Problems

The considerations and speculations noted above lead to four main areas where knowledge is needed and policy action should be taken to adapt human activities to impending climate change in northern regions. The issues and problems can be posed briefly in a set of questions and areas for policy and research attention.

1. *The Role of High Latitude Processes in Determining Regional or Global Climatic Response to Increases in Greenhouse Gases*

(1.1) What are the patterns, rates, and degrees of stability of energy and mass transfer mechanisms that distribute energy from the tropics to high latitudes? How do these mechanisms serve to dampen, or to amplify, climate perturbations due to increase of greenhouse gases released principally in northern mid-latitudes?

(1.2) What is the relation between changes in high-latitude albedo (increase or decrease of net areas of snow and ice) and surface temperature?

(1.3) Are there identifiable thresholds or steps in the relationship between incoming and outgoing radiation, albedo, and surface temperature that are critical to the maintenance of a regional sea ice cover? How vulnerable are these relationships to perturbations caused by rapid increase in greenhouse gases? Which are the critical variables?

(1.4) What are the consequences to global climate of rapid disappearance of arctic sea ice? What are the consequences of gradual shrinking of the ice cover? To what degree, if any, would these global effects be reinforced or counterbalanced by events in the south polar regions?

(1.5) What are the effects that greenhouse warming of global air surface temperatures may have on the behaviour of the local areas of increased heat transfer between the atmosphere and the ocean that are found in high latitudes, and thus on the formation of cold bottom waters that ultimately regulate the long-term ocean climate?

(1.6) What would be the effect on sea level of the mass changes in the Greenland and Antarctic icecaps that would be brought about by rapid climate warming due to increase in greenhouse gases? For a given rate of climate warming, how quickly will the glacier melt water response affect world sea level? What is the relationship, in the arctic and antarctic areas, between the increased cloudiness and precipitation brought about by climate warming and the increased melting?

2. *The Effect that Global Climate Warming Due to Increase in Greenhouse Gases in the Present and Next Century Will Have on Northern Regions*

(2.1) What are the expected changes in vigor, temperature and pattern of the North Atlantic Drift, especially its dispersal and heat transport across the Barents Sea and/or through the West Spitzbergen Current? What factors determine stability or sensitivity of the volume, velocity, and pattern of the Drift under changing surface thermal balance?

(2.2) What changes in north polar atmospheric circulation can be expected,

how quickly, and how would these affect wind patterns in the Arctic Ocean and adjacent seas? How would these changes affect:
- the distribution of ice and open water;
- cloudiness and cloud patterns, and energy exchange at the sea and land surface;
- the pattern, timing, and depth of snowfall on land and sea ice;
- the resultant heat loss to space, because of changes in the thermal blanket of snow on land and sea ice?

(2.3) What effects will small changes of sea level have on northern coastal areas, and their marine, hydrological or biological systems?

(2.4) What is the relationship between average and extreme temperatures, available photosynthetic energy, and nutrient supply in limiting biological production in 'biologically important' parts of northern seas and lands? Which of these factors are most affected by the postulated climate change and or changes in radiation spectrum with increase in greenhouse gases?

(2.5) What are the combinations of topography, nutrient supply and microclimate that control northern biological productivity; and in what ways are these sensitive to the postulated climate change?

(2.6) What is the relative and absolute role that localized "northern oases" or areas of high productivity play in northern ecosystems? How sensitive is this role to the postulated changes of climate, and over what time periods would the effect be felt?

(2.7) What are the rates and ranges of dispersal, colonization or die-off among key species in northern biological communities under climate-driven changed environmental conditions? What changes in biological communities or biological succession will signal adaptation to or disruption by climate change?

3. *Identification of Local, National, or International Policies That Are or Could Be Sensitive to Climate Change in High Latitudes*

Policies in the following subject areas can be expected to be affected by change of climate in northern regions. Some may be relevant also to climate changes in Antarctica, southern South America and Australasia. For each policy area, careful consideration should be given to the manner in which specific climate-driven environmental changes will influence policies in both the short and longer term.

(3.1) Policies related to local planning and resource development.

(3.2) Policies related to regional or activity-specific industrial development, investment, and trade.

(3.3) Policies related to environmental protection, and the long-term investment in renewable natural resources.

(3.4) Policies related to education and awareness of environmental changes and the opportunities and constraints they present. These policies may be the most important of all, for they will influence how the next generation will adapt to and take advantage of new climatic conditions.

(3.5) Policies related to equity and justice for all parts of society, especially for the sub-cultures or sections of society that have different environmental values or whose livelihoods/life styles are more sensitive to climate change. If allowed to respond in their own way but fully linked to the modern communications systems, the less industrialized sub-cultures of northern regions may well be better able to take positive advantage of the changed conditions than the mainstream societies that are more dependent on technology and complex institutions.

(3.6) Policies for compensation or aid for those affected by natural disasters, as well as for prior investment to guard against the unwanted effects of the physical and biological manifestations of climate change; or similar policies to help citizens and industry take advantage of the new conditions.

(3.7) Policies related to management of the global commons (e.g. Law of the Sea), or internationally shared resources (e.g. the Polar Bear Treaty or the Migratory Birds Convention) as they are affected by climate change.

(3.8) National or geopolitical policies and strategies related to surveillance, security, or military operations on land, sea, and air in northern regions, and the effect of changes in snow, sea ice, and atmospheric conditions on the technologies and tactics of defense.

4. *Areas for Attention in Developing a Technical Agenda for Linking Problems and Issues Related to Climate Change with Policies in Northern Regions*

(4.1) Process studies of arctic biological-geophysical interactions, especially rates, space scales, and variabilities.

(4.2) Comparative studies of biological-geophysical interactions in different local and micro-climatological settings, over extended periods, focussing especially on ecotones, environmental or inter-community interfaces or successions, and energy and chemical flows between trophic levels.

(4.3) Studies of environmental and ecological responses in northern regions to climate fluctuations in the past and to human disturbances in recent decades.

(4.4) Development of regional or meso-scale models of climate fluctuations that simulate the characteristics and interactions of solid precipitation (both snowfall and ice-crystal deposition), blowing snow as a mechanism of material and energy transport, arctic cloud types, and the insulative properties of a range of snow depths and sea ice thicknesses.

(4.5) Development of air/sea/ice models that effectively take into account heat and moisture transfer through open leads and polynyas, and terrestrial air/land/permafrost models for tundra and boreal forest that simulate seasonal year-to-year, and decadal variations under postulated climate change.

(4.6) Development of models of northern hydrological systems or selected watersheds that will explore the effects of climate change.

(4.7) Incorporation of climate change parameters into economic models for resource development, land use, or regional planning.

(4.8) Consideration of the lessons to be learned from past human experience of environmental change in northern regions: studies of the responses of indigenous societies to the changes in resources and environmental conditions caused by climate fluctuations in the past; comparative studies of the adaptation of different northern societies to different environmental conditions in various circumpolar areas. Key responses to be studied should include social behaviour, population control, resources utilization and, knowledge transfer development or adaptation of technology.

References

Aagaard, K.: 1982, 'Inflow from the Atlantic Ocean to the Polar Basin', in L. Rey and B. Stonehouse (eds.), *The Arctic Ocean: The Hydrographic Environment and the Fate of Pollutants*, MacMillan, London, pp. 69–81.

Aagaard, K., Carmack, E. C., Foldvik, A., Killworth, P. D., Lewis, E. C., Meinke, J., and Paulsen, C. A.: 1979, *The Arctic Ocean Heat Budget*, Report No. 52 from SCOR Working Group 58, University of Bergen, 97 pp.

Aagaard, K. and Greisman, P.: 1975, 'Toward New Mass and Heat Budgets for the Arctic Ocean', *J. Geophys. Res.* **80**, 3821–3827.

Andrews, J. T.: 1972, 'Recent and Fossil Growth Rates of Marine Bivalves in Canadian Arctic and Late-Quarternary Arctic Marine Environments', *Palaeogeography, Palaeoclimatology, Palaeoecology* **11** (3), 157–176.

Arrhenius, S.: 1896, 'On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground', *Philosophical Magazine* **41**, 237–250.

Baker, J. M. and Angel, M. V.: 1987, 'Marine Processes' in J. G. Nelson *et al.* (eds.), *Arctic Heritage*, Assoc. Can. Univ. for Northern Studies, pp. 80–94.

Barry, R. G. and Hare, F. K.: 1975, 'Arctic Climate' in J. D. Ives and R. G. Barry (eds.), *Arctic and Alpine Environments*, Methuen, London, pp. 17–54.

Benson, C. S. and Bowling, S. A.: 1975, 'The Sub-Arctic Urban Heat Island as Studied at Fairbanks, Alaska', in G. Weller and S. A. Bowling (eds.), *Climate of the Arctic*, Geophys. Inst. Univ. Alaska, pp. 309–311.

Bentley, C. R.: 1985, 'Glaciological Evidence: the Ross Sea Sector', in M. F. Meier *et al.* (eds.) *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change*, U.S. Dept. of Energy, pp. 172–177.

Bindschadler, R. A.: 1985, 'Contribution of the Greenland Ice Cap to Changing Sea Level: Present and Future', in M. F. Meier *et al.* (eds.), *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-Induced Climatic Change*, U.S. Dept. of Energy, pp. 258–266.

Blake, W. Jr.: 1972, 'Climatic Implications of Radiocarbon-dated Driftwood in the Queen Elizabeth Islands, Arctic Canada', in Y. Vasari *et al.* (eds.), *Climatic Changes in Arctic Areas during the Last Ten Thousand Years.* Acta Universitatis Ouluensis, Ser. A., Geologica (1), pp. 78–104.

Bliss, L. C. (ed.): 1977, *Truelove Lowland, Devon Island, Canada: A High Arctic Ecosystem*, University of Alberta Press, Edmonton, 714 p.

Bliss, L. C., Heal, O. W., and Moore, J. J. (eds.): 1981, *Tundra Ecosystems: A Comparative Analysis*, Cambridge Univ. Press, Cambridge, 450 p.

Bolin, B., Doos, B. R., Jaeger, J., and Warwick, R. A. (eds.): 1986, *The Greenhouse Effect, Climate Change, and Ecosystems: A Synthesis of Present Knowledge*. SCOPE **29**, J. Wiley and Sons, Chichester, 579 p.

Bolle, H. J., Seiler, W., and Bolin, B.: 1986, 'Other Greenhouse Gases' in B. Bolin *et al.* (eds.), *The Greenhouse Effect, Climate Change, and Ecosystems: A Synthesis of Present Knowledge*. SCOPE **29**, pp. 93–156.

Budd, W. F. and Smith, I. N.: 1985, 'The State of Balance of the Antarctic Ice Sheet – An Updated Assessment 1984' in M. F. Meier *et al.* (eds.), *Glaciers, Ice Sheets and Sea Level: Effect of a CO_2-Induced Climatic Change*, U.S. Dept. of Energy, pp. 172–177.

Callaghan, T. V., and Collins, N. J.: 1981, 'Life Cycles, Population Dynamics and the Growth of Tundra Plants', in L. C. Bliss *et al.* (eds.), *Tundra Ecosystems: A Comparative Analysis*, Cambridge University Press, pp. 257–284.
Chapin, F. S., Miller, P. C., Billings, W. D., and Coyne, P. I.: 1980, Carbon and Nutrient Budgets and their Control in Arctic Tundra', in J. Brown *et al.* (eds.), *An Arctic Ecosystem; the Coastal Tundra at Barrow, Alaska.* Dowden, Hutchison and Ross, Stroudsburg, pp. 458–482.
Clark, D. L.: 1982, 'Origin, Nature and World Climate Effect of the Arctic Ocean Ice-Cover', *Nature* **300**, 321–324.
Cooch, F. G., Funn, A., and Stirling, I.: 1987, 'Faunal Processes' in J. G. Nelson *et al.* (eds.), *Arctic Heritage*, Assoc. Can. Univ. for Northern Studies, pp. 95–111.
Dansgaard, W., Johnson, S. J., Clausen, H. B., and Langway, C. C.: 1971, 'Climate Record Revealed by the Camp Century Ice Core' in K. Turekian (ed.), *Late Cenozoic Glacial Ages*, Yale Univ. Press, New Haven, pp. 37–56.
Davis, M. B. and Botkin, D. B.: 1985, 'Sensitivity of Cool-Temperate Forests and their Fossil Record to Rapid Temperature Change', *Quaternary Research* **23**, 327–340.
Dunbar, M. J.: 1979, *Ecological Development in Polar Regions – A Study in Evolution*, Prentice-Hall, Englewood Cliffs, N.J., 119 pp.
Dunbar, M. J.: 1982, 'Arctic Marine Ecosystems', in L. Rey and B. Stonehouse (eds.), *The Arctic Ocean: The Hydrographic Environment and the Fate of Pollutants*, Macmillan, London, pp. 233–261.
Dunbar, M. J.: 1983, 'A Unique International Polar Year Contribution: Lucien Turner, Capelin, and Climate Change' *Arctic* **36** (2), 204–205.
Dunbar, M. J. and Thompson, D. H.: 1979, 'West Greenland Salmon and Climate Change', *Meddelelser om Grønland* **202** (4), 5–19.
Edlund, S. A.: 1986, 'Modern Arctic Vegetation Distribution and Its Congruence with Summer Climate Patterns' in H. M. French (ed.), *Climate Change Impacts on the Canadian Arctic*, Atmospheric Environment Service, Ottawa, pp. 84–99.
Farmer, R. E., Knowles, P., and Parker, W. H.: 1983, 'Genetic Resources of the North American Boreal Forest' in R. W. Wein *et al.* (eds.), *Resources and Dynamics of the Boreal Zone*, Assoc. Can. Univ. for Northern Studies, pp. 40–51.
Flohn, H.: 1981, *Life on a Warmer Earth*, International Institute for Applied Systems Analysis, Laxenburg, Austria, Report ER-3, 40 p.
French, H. M. (ed.): 1986, *Climate Change Impacts on the Canadiann Arctic*, Atmospheric Environment Service, Ottawa, 171 pp.
Friedman, E. I. and Kibler, A. P.: 1980, 'Nitrogen Economy of Endolithic Microbial Communities in Hot and Cold Deserts', *Microbial Biology* **6** (2), 95–108.
Golikov, A. N. and Averincev, V. G.: 1977, 'Distribution Patterns of Benthic and Ice Biocoenoses in the High Latitudes of the Polar Basin and their Part in the Biological Structure of the World Ocean', in M. J. Dunbar (ed.), *Polar Oceans*, Arctic Inst. of North America, pp. 331–364.
Gunn, A., Decker, R., and Barry, T. W.: 1984, 'Possible Causes and Consequences of an Expanding Muskox Population, Queen Maud Gulf Area, Northwest Territories', in D. R. Klein *et al.* (eds.), *Proceedings of the First International Muskox Symposium*, Univ. Alaska Biol. Report No. **4**, pp. 41–46.
Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fury, I., Ruerly, R., and Lerner, J.: 1984, 'Climate Sensitivity: Analysis of Feedback Mechanisms', in J. Hansen and T. Takahashi (eds.), *Climate Processes and Climate Sensitivity*, Maurice Ewing Monograph Series 5, Amer. Geophys. Union, Washington, pp. 348–368.
Hare, F. K. and Thomas, M. K.: 1974, *Climate Canada*, Wiley, Toronto, 256 pp.
Harington, C. R.: 1986, 'The Impact of Changing Climate on Some Vertebrates in the Canadian Arctic', in H. M. French (ed.), *Climate Change Impacts on the Canadian Arctic*, Atmospheric Environment Service, Ottawa, pp. 100–113.
Harriss, R. C., Gorham, E., Sebacher, D. I., Bartlett, K. G., and Flebbe, P. A.: 1985, 'Methane Flux from Northern Peatlands', *Nature* **315**, 652–653.
Hampel, G.: 1985, 'On the Biology of the Polar Seas, Particularly the Southern Ocean', in J. S. Gray and M. E. Christiansen (eds.), *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms*, John Wiley, New York, pp. 31–35.

Holmgren, B. and Weller, G.: 1974, 'Local Radiation Fluxes over Open and Freezing Leads in the Polar Pack Ice', *AIDJEX Bulletin*, Univ. of Washington, No. 27, pp. 149–166.

Houghton, J. T. (ed.): 1984, *Global Climate*, Cambridge Univ. Press, Cambridge, 564 pp.

Jacobs, S. S.: 1985, 'Oceanographic Evidence for Land Ice-Ocean Interaction in the Southern Ocean' in M. F. Meier *et al.* (eds.), *Glaciers, Ice Sheets and Sea Level: Effect of a CO_2-Induced Climate Change*, U.S. Dept. of Energy, pp. 116–128.

Jezek, K. C. and Bentley, C. R.: 1984, 'A Reconsideration of the Mass Balance of a Portion of the Ross Ice Shelf', *Jour. Glaciology* **30** (106), 381–384.

Johnson, L.: 1976, 'Ecology of Arctic Populations of Lake Trout, Lake Whitefish, and Arctic Char and Associated Species in Unexploited Lakes of the Canadian Northwest Territories', *J. Fish Res. Bd. Can.* **33** (11), 2459–2488.

Kauppi, P., and Posch, M.: 1985, 'Sensitivity of Boreal Forests to Possible Climate Warming', *Climatic Change* **7**, 45–54.

Kay, P. A.: 1978, 'Dendroecology in Canada's Forest-Tundra Transition Zone', *Arctic and Alpine Research* **10** (1), 133–138.

Kellogg, W. W.: 1981, 'Climate Change and Society: Environmental Effects and Social Consequences of Climate Change Induced by Increasing Carbon Dioxide', in *Climate Change Seminar Proceedings, Regina, Saskatchewan*, Atmospheric Environment Service, Ottawa, pp. 129–153.

Kils, U.: 1983, 'The Swimming Behaviour, Swimming Performance, and Energy Balance of Antarctic Krill, Euphausia Superba', *BIOMASS Scientific Series*, No. 3, 122 p.

Knox, G. A. and Lowry, J. K.: 1977, 'A Comparison Between Benthos of the Southern Ocean and the North Polar Ocean with Special Reference to the Amphipoda and Polychaeta' in M. J. Dunbar (ed.), *Polar Oceans*, Arctic Inst. of North America, pp. 423–462.

Kuhn, M.: 1981, 'Climate and Glaciers', in I. Allison (ed.), *Sea Level, Ice, and Climate Change*, Internat. Assoc. of Hydrological Sciences, Pub. No. 131, pp. 3–20.

Lachenbruch, A. H. and Marshall, B. V.: 1986, 'Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic', *Science* **234**, 689–696.

Lamb, H. H.: 1982, 'The Climatic Environment of the Arctic Ocean', in L. Rey and B. Stonehouse (eds.), *The Arctic Ocean: The Hydrographic Environment and the Fate of Pollutants*, Macmillan, London, pp. 135–161.

Larsen, J. A. and Barry, R. G.: 1974, 'Palaeoclimatology', in J. D. Ives and R. G. Barry (eds.), *Arctic and Alpine Environments*, Methuen, London, pp. 253–276.

Lindsay, D. G.: 1976, 1981, *Sea Ice Atlas of Arctic Canada 1961–1968; Sea Ice Atlas of Arctic Canada, 1969–1974; Sea Ice Atlas of Arctic Canada, 1975–1978*, Dept. of Energy Mines and Resources, Ottawa, 3 Vols.

Manabe, S. and Stouffer, R. J.: 1980, 'Sensitivity of a Global Climate Model to Increase of CO_2 Concentration in the Atmosphere', *J. Geophys. Research* **85**, 5529–5554.

Macpherson, J. B.: 1985, 'The Postglacial Development of Vegetation in Newfoundland and Eastern Labrador-Ungara: Synthesis and Climatic Interpretations', in C. R. Harington (ed.), *Critical Periods in the Climatic History of Northern North America*, Syllogeus, **55**, Climate change in Canada Series 5, National Museums of Canada, pp. 267–280.

Mathews, B.: 1967, 'Late Quarternary Marine Fossils from Frobisher Bay (Baffin Island, NWT, Canada)', *Palaeogeography, Palaeoclimatology, Palaeoecology* **3** (2), 243–263.

Mathews, J. V.: 1976, 'Arctic Steppe: An Extinct Biome', *American Quarternary Association, National Conference 1976*, 73–79.

Maxwell, J. B.: 1980, *The Climate of the Canadian Arctic Islands and Adjancent Waters*, Atmospheric Environment Service, Climatological Series No. 30, Vol. 1, Ottawa, 532 pp.

McCart, P. J. and Den Beste, J.: 1979, *Aquatic Resources of the Northwest Territories*, Science Advisory Board of the Northwest Territories, Yellowknife, 59 pp.

McKay, G. A. and Baker, W. M.: 1986, 'Socioeconomic Implications of Climate Change in the Canadian Arctic', in H. M. French (ed.), *Climate Change Impacts on the Canadian Arctic*, Atmospheric Environment Service, Ottawa, pp. 116–136.

Meier, M. F.: 1984, 'Contribution of Small Glaciers to Global Sea Level', *Science* **226**, 1418–1421.

Meier, M. F., Aubrey, D. G., Bentley, C. R., Broecker, W. S., Hansen, J. E., Peltier, W. R., and Somerville, R. G. J.: 1985, 'Probable Land-Ice and Ocean Exchanges during the Next 100 Years, Antarc-

tica', in M. F. Meier *et al.* (eds.), *Glaciers, Ice Sheets and Sea Level: Effect of a CO_2-Induced Climate Change*, U.S. Dept. of Energy, pp. 46–58.
Newton, C. W.: 1972, 'Southern Hemisphere General Circulation in Relation to Global Energy and Moisture Balance Requirements', *Meteorological Monographs, Amer. Meteorol. Soc.* **13** (35), 215–246.
Nichols, H.: 1975, 'Palynological and paleoclimatic study of the late Quaternary displacements of the boreal forest-tundra ecotone in Keewatin and Mackenzie,, N. W. T., Canada', *Arctic and Alpine Research*, Occasional Paper **15**, 1–87.
Oerlemans, J. and Van der Veen, C. J.: 1984, *Ice Sheets and Climate*, Kluwer Acad. Publ., Dordrecht, The Netherlands, 217 pp.
Oliver, D. R.: 1964, 'A Limnological Investigation of a Large Arctic Lake, Nettilling Lake, Baffin Island', *Arctic* **17** (2), 69–83.
Oort, A. H.: 1985, 'Year-to-year Variations in the Energy Balance of the Arctic Atmosphere', in G. Weller and S. A. Bowling, (eds.), *Climate of the Arctic*, Geophys. Inst. Univ. Alaska, pp. 68–75.
Pennington, W.: 1986, 'Lags in Adjustment of Vegetation to Climate Caused by the Pace of Soil Development', *Vegetatio* **67**, 105–118.
Péwé, T. L. and Brown, J. (eds.): 1984, *Permafrost-Proceedings of the Fourth International Conference*, National Academy Press, 2 Vols., 1936 p.
Plass, G. N.: 1956, 'The Carbon Dioxide Theory of Climate Change', *Tellus* **8**, 140–154.
Polar Research Board: 1983, 'Snow and Ice Research: An Assessment', *Committee on Glaciology, Polar Research Board, National Research Council*, National Academy Press, Washington, 126 pp.
Price, P. G.: 1975, 'Comparison between Available Potential and Kinetic Energy Estimates for the Southern and Northern Hemisphere', *Tellus* **27** (5), 443–452.
Revelle, R. and Suess, H. E.: 1957, 'Carbon Dioxide Exchange between Atmosphere and Ocean, and the Question of an Increase of Atmospheric CO_2 during Past Decades', *Tellus* **9**, 18–27.
Ritchie, J. C. and Hare, F. K.: 'Late Quaternary Vegetation and Climate near the Arctic Tree Line of Northwestern North America', *Quaternary Research* **1** (3), 331–342.
Roots, E. F.: 1979, *Lancaster Sound: Issues and Responsibilities*, Canadian Arctic Resources Committee, Ottawa, 107 pp.
Roots, E. F.: 1982, 'The Changing Arctic Marine Environment', in L. Rey and B. Stonehouse (eds.), *The Arctic Ocean: The Hydrographic Environment and the Fate of Pollutants*, Macmillan, London, pp. 215–232.
Roots, E. F.: 1986, 'Policy Implications of Climate Change in Arctic Regions', in H. M. French (ed.), *Climate Change Impacts on the Canadian Arctic*, Atmospheric Environment Service, Ottawa, pp. 146–169.
Roots, E. F.: 1987, 'The Natural Realm and Arctic Heritage', in J. G. Nelson *et al.* (eds.), *Arctic Heritage*, Assoc. Can. Univ. for Northern Studies, pp. 164–176.
Sancetta, C., Imbrie, J., and Kipp, N. G.: 1973, 'Climatic Record of the Past 130,000 Years in North Atlantic Deep-Sea Core V23-82: Correlation with the Terrestrial Record', *Quaternary Research* **3** (1), 110–116.
Schelling, T. C.: 1983, 'Climate Change: Implications for Welfare and Policy', in *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, U.S. National Research Council, National Academy Press, Washington, Chapter 9.
Serpalov, S. T.: 1969, 'Atmospheric Circulation in the Southern Hemisphere and Synoptic Processes in the Antarctic', *Israel Program for Scientific Translations*, TT69-55805, pp. 109–120.
Siedel, S. and Keys, D.: 1983, *Can We Delay a Greenhouse Warming?*, U.S. Environmental Protection Agency, 192 pp.
Singh, T. and Powell, J. M.: 1986, 'Climatic Variations and Trends in the Boreal Forest Region of Western Canada', *Climatic Change* **8**, 267–278.
Smith, M.: 1986, 'The Significance of Climate Change for the Permafrost Environment', in H. M. French (ed.), *Climate Change Impacts on the Canadian Arctic*, Atmospheric Environment Service, Ottawa, pp. 67–81.
Smith, W. O. and Nelson, D. M.: 1985, 'Phytoplankton Bloom Produced by a Receding Ice Edge in the Ross Sea: Spatial Coherence with the Density Field', *Science* **227**, 163–166.

Svoboda, J. and Henry, G. H. R.: 1987, 'Succession in Marginal Arctic Environments', *Arctic and Alpine Research* **19** (4), 373–384.

The Polar Group: 1980, 'Polar Atmosphere-Ice-Ocean Processes: A Review of Polar Problems in Climate Research', *Rev. Geophysics and Space Physics* **18** (2), 525–543.

Thomas, V. G. and MacDonald, S. D.: 1987, 'The Significance of Terrestrial and Marine Oases in the High Arctic', in J. G. Nelson *et al.* (eds.), *Arctic Heritage*, Assoc. Can. Univ. for Northern Studies, pp. 147–153.

Timofeyev, V. T.: 1962, 'The Movement of Atlantic Water and Heat into the Arctic Basin', *Deep-Sea Research* **9**, 358–361.

Untersteiner, N.: 1982, 'The Sea Ice-Air Interface', in L. Rey and B. Stonehouse (eds.), *The Arctic Ocean: The Hydrographic Environment and the Fate of Pollutants*, Macmillan, London, pp. 113–129.

USSR: 1986, 'On Stopping Work in the Diversion of Part of the Flow of Northern and Siberian Rivers', *Decrees of the Central Committee of the Communist Party of the Soviet Union and the Council of Ministers of the USSR*, First Section, 1986, No. 29, Article 158, pp. 517–518 (in Russian). (Similar companion decree enacted by the Council of Ministers of the Russian Soviet Federated Socialist Republic, No. 25, Article 187, pp. 498–499).

Von der Haar, T. H. and Oort, A. H.: 1973, 'New Estimates of Annual Poleward Energy Transport by Northern Hemisphere Oceans', *J. Physical Oceanog.* **3**, 169–172.

Vowinkel, E., and Orvig, S.: 1970, 'The Climate of the North Polar Basin', in S. Orvig (ed.), *Climates of the Polar Regions*, World Survey of Climatology, Vol. 14, Elsevier, Amsterdam, pp. 129–252.

Webber, P. J.: 1978, 'Spatial and Temporal Variation of the Vegetation and its Productivity', in L. L. Tiezen (ed.), *Vegetation and Production Ecology of an Alaskan Arctic Tundra*, Springer-Verlag, New York, pp. 37–112.

Weertman, J.: 1974, 'Stability of the Junction of an Ice Sheet and an Ice Shelf', *J. Glaciology* **13**, 3–11.

Weilgolaski, F. E.: 1987, 'Floral Processes', in J. G. Nelson *et al.* (eds.), *Arctic Heritage*, Assoc. Can. Univ. for Northern Studies, pp. 80–94.

Wein, R. W. and El-Bayoumi, M. A.: 1983, 'Limitations to Predictability of Plant Succession in Northern Ecosystems' in R. W. Wein *et al.* (eds.), *Resources and Dynamics of the Boreal Zone*, Assoc. Can. Univ. for Northern Studies, pp. 214–225.

Weller, G., Bowling, S. A., Holmgren, B., Jayaweera, K., Ohtake, T., and Shaw, G.: 1975, 'The Radiation Matrix in the Arctic', in G. Weller and S. A. Bowling (eds.), *Climate of the Arctic*, Geophys. Inst. Univ. of Alaska, pp. 238–244.

World Meteorological Organization: 1982, *Report of the WMO/CAS-JSC-CCCO Meeting of Experts on the Role of Sea Ice in Climate Variations, with Special Reference to Antarctica*, World Meteorological Organization, Report WCP-26.

World Meteorological Organization: 1986, *Report of the International Conference on the Assessment of the Role of Carbon Dioxide and other Greenhouse Gases on Climate Variations and Associated Impacts*, World Meteorological Organization, Geneva, Report WMO-661.

Zwally, H. J., Parkinson, C. C., and Comisa, J. C.: 1981, 'Variability of Antarctic Sea Ice and CO_2 Change', *Science* **220**, 1005–1012.

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