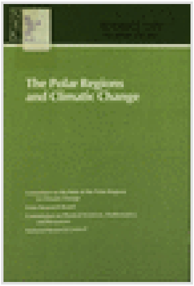

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National Research Council

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Foreword

This document is one of a series issued by the Polar Research Board that identifies needs and develops strategies for polar research. These studies are expected to be sufficiently searching to guide polar research over the next two decades. The setting of priorities is particularly important in times of financial stress, and it is hoped that these studies will assist the decision makers who will be doing so in government and nongovernment organizations concerned with the polar regions.

Six studies in the series have now been completed: An Evaluation of Antarctic Marine Ecosystem Research; Study of the Upper Atmosphere and Near-Earth Space in Polar Regions: Scientific Status and Recommendations for Future Directions; Polar Biomedical Research. An Assessment, with an Appendix, Polar Medicine--A Literature Review; Snow and Ice Research. An Assessment; Permafrost Research: An Assessment of Future Needs; and this one. Work continues on two other studies, with further studies to be initiated during the coming year.

The Polar Research Board greatly appreciates the work of J. Murray Mitchell, Jr., and William W. Kellogg, Cochairmen of the ad hoc Committee on The Role of the Polar Regions in Climatic Change, and of the members of this committee in the conduct of the study and the preparation of this report on their findings and recommendations.

Charles R. Bentley, Chairman
Polar Research Board

Preface

The climate of the Earth is perpetually variable and changing. Uncertainties about future climate, compounded by concerns that the accumulation of carbon dioxide in the atmosphere and other by-products of human activities may bring about inadvertent changes of climate in future decades, place a premium on improved understanding and prediction of climate to meet the needs of modern society. A major goal of climate research now in progress under the aegis of many national and international institutions is to develop a comprehensive theory of global climate as a first step to a rational climate prediction capability. Significant progress toward this goal has been achieved in the past decade.

In connection with global climate concerns, the polar regions of the Earth have become the focus of considerable attention in view of three distinct yet related circumstances:

- Growing evidence that the polar regions play a key role in the physical processes responsible for global climatic fluctuations and in some circumstances may be a prime mover of such fluctuations;
- Widening appreciation of the polar regions as a natural repository of information about past climatic fluctuations and about past Earth-environmental events causally related to climatic fluctuations; and
- Mounting concerns that future changes of climate, such as the general global-scale warming believed likely to result in future decades and centuries from the accumulation of carbon dioxide and other pollutants in the atmosphere, may disturb the equilibrium of polar ice masses and hence global sea levels.

These several matters clearly merit intensive parallel study based on separate research agendas. At the same time, however, the Polar Research Board of the National Research Council (NRC) has perceived a need to address them together in the context of a holistic view of planetary-scale climate, from which perspective the global interconnectedness of climate processes and their social implications is both the unifying theme and the key to setting overall goals and priorities in climate-related polar research. This perspective and its implications for future research are the focus of this report. The report is intended to present a general overview of the basic research needs in its broadest terms. In many cases, the specific details and plans of actions can be found in companion Polar Research Board reports of more specialized scope, either already published or now in preparation.

The report was prepared by the Committee on the Role of the Polar Regions in Climatic Change, which was established by the Polar Research Board in 1980 to undertake a study in the Board's new "Polar Research - A Strategy" series. The organization of this committee was encouraged by the NRC's Climate Board (now the Board on Atmospheric Sciences and Climate). The Committee was charged with reviewing the state of knowledge about polar processes in global climate dynamics, identifying research needs, and recommending directions for future research. It was asked to give particular attention to the implications of predicted climatic changes resulting from increasing levels of atmospheric carbon dioxide for the stability of the polar ice sheets.

The committee's report presents its findings, conclusions, and recommendations. A separate volume will contain three signed appendixes that cover detailed background material on The Role of the Polar Regions in Climate Dynamics (J.O. Fletcher and U. Radok), Polar Regions as Windows on the Past (J.D. Hays, J.T. Andrews, C.C. Langway, and T.L. Péwé), and The Polar Regions: A Concern for the Future (C.R. Bentley, R.G. Barry, J.H. Mercer, and T.J. Hughes).

Contents

Executive Summary

BACKGROUND

Present-day conditions of global climate are but a transitory balance between the predominantly colder conditions prevailing during the Quaternary ice age, the relative warmth of an interglacial interlude occupying the last 10,000 years, and a welter of more rapid climatic fluctuations that continually sweep our planet. The causes of these fluctuations of widely differing time scale and character are essentially unknown. Earth-orbital changes, variability of the sun, volcanic eruptions affecting atmospheric transparency, and other environmental disturbances probably all play a part. However, much of the variability of climate is likely self-generated by various dynamic imbalances arising between different parts of the "climate system": the atmosphere, oceans, and ice and land masses. These imbalances maintain the system in a continual state of unrest on time scales ranging from weeks for the atmosphere to tens of thousands of years for the continental ice sheets.

To achieve quantitative understanding of the physical, chemical, and biological processes that contribute to climate-system variability will require comprehensive theoretical models of the system that are capable of simulating its complex time-dependent behavior. So far, only in limited respects has the time-dependent behavior of the climate system been modeled well enough to have clear interpretive or predictive value. Improved models are especially needed to assess the likely character of future climatic changes, including those related to future increases of carbon dioxide (CO_2) and other "greenhouse" gases in the atmosphere.

POLAR REGIONS AS SOURCES OF CLIMATIC UNREST

Ice and snow conditions in the polar regions are highly sensitive to variations of climate. Changes in those conditions then feed back to disturb the climate. In both polar areas, changes of sea ice profoundly alter the flow of heat from the oceans to the polar atmosphere. In the Antarctic, sea-ice conditions also influence the atmospheric circulation over the ice sheet, including the strong katabatic winds of the region, and hence modulate the effectiveness of the Antarctic continent as a global "heat sink." Changes of snow cover further affect the seasonal changes of heating and survival of sea ice in polar areas. In these and other ways the polar regions induce transient imbalances of the planetary heat budget that are the source of fluctuations in both atmospheric and oceanic conditions in lower latitudes, on time scales ranging from months to centuries.

To establish the full extent of involvement of polar processes in the behavior and causation of global climate variability and change requires a better understanding of the dynamics of the climate system as a whole, including a quantitative grasp of the longer-term interactions among oceans, ice masses, and atmosphere, and of the way these interactions differ in the Arctic and the Antarctic.

We conclude that two principal focuses for future research are needed in this field:

o The development of models of the global climate system with special attention to improved simulation of climatic processes in the polar regions, and

o Better understanding of the global-scale response of the oceans to atmospheric changes in polar and subpolar latitudes.

In regard to climate-system <u>modeling</u>, we <u>recommend</u>:

1. Continued efforts to improve the manner in which various polar processes are simulated in current climate-system models, including

(a) the response of sea ice to atmospheric and oceanic changes,

(b) atmospheric effects of snow cover and sea ice,

(c) effects of polar cloudiness on the surface and atmospheric heat balance,

(d) the relationship of air-sea interactions to ice in polar regions, and

(e) ice-sheet dynamics and the response of ice sheets to atmospheric and oceanic changes.

2. Simulation in future climate-system models of processes and phenomena not now adequately addressed that affect the growth and decay of ice sheets, including:

(a) low-level inversions and associated katabatic winds over the Antarctic ice sheet together with their effects,

(b) blowing snow and sublimation as they affect the mass balance of ice sheets and energy fluxes across their boundaries and between their various parts, and

(c) precipitation over the ice sheets as distinguished between snowfall (from high-latitude storm systems) and ice-crystal deposition ("diamond dust" under clear-sky conditions).

3. Special attention to atmospheric blocking patterns and their variations in frequency.

4. Study, through climate models, of conditions that would favor the coexistence of a glaciated Antarctic and a seasonally ice-free Arctic and its implications for the climate of lower latitudes.

In regard to the <u>oceanic response</u> to atmospheric change in polar regions, we <u>recommend</u>:

1. Field studies and appropriate modeling strategies to determine the nature of the response of the ocean to changes in polar atmospheric conditions and the processes involved in the response, including the part played by sea ice.

2. Study of variations in the production and transport of intermediate and bottom ocean-water masses as a potential source of persistent sea-surface temperature anomalies in lower latitudes and of related long-term global climatic fluctuations, based on

(a) analyses of the record of sea-surface temperatures,

(b) chemical and radioisotope measurements tracing the history and trajectories of water masses, and

(c) ocean models capable of simulating the movement and transformation of ocean water masses.

POLAR REGIONS AS WINDOWS ON THE PAST

Considerable progress has been made in constructing a quantitative record of past climates and climate-related phenomena from analyses of ocean-floor sediments, ice sheets, and the tundra and boreal zones of the far north. Such analyses have shed new light on the physical behavior of the climate system, on the causal mechanisms of climatic change, and on the range of possibilities for future change. They have also been useful in testing under a wide range of environmental conditions the validity of climate-system models used to explore the physical mechanisms of climatic change and the feasibility of climate prediction.

The potential of the polar regions to supply additional insights into past climatic variations and into the physical processes responsible for them far exceeds what has already been exploited. That potential justifies a continuing program of vigorous research along several parallel lines. In particular, we recommend:

1. Continued analyses of available ocean-bottom cores to determine past distributions of sea ice and their fluctuations, and to refine time-control techniques for increased precision of absolute dating and inter-hemispheric correlation of climatic events.
2. Collection of longer, high-deposition-rate cores of ocean-floor sediments in high-latitude areas to improve the time resolution of climatic variations reflected in the sediments and to extend the record of past climates.
3. Continued acquisition and analysis of polar ice cores over the coming decade, including
    (a) development of fast-operating, lightweight ice-core drilling devices for both shallow and intermediate coring, as well as fuller exploitation of present deep-drilling technology and
    (b) a geographically broadened ice-coring program in both polar areas, balanced among shallow, intermediate, and deep-coring activites, with provision for a strong laboratory core-analysis capability.
4. An intensified program of pollen analysis of sediments in tundra and boreal zones, with the objectives of improving understanding of the geographic distribution of current pollen "rain" in the Arctic and sub-Arctic areas as necessary to the calibration of past pollen changes, providing a more detailed history of vegetation

and climate in the Holocene and pre-Holocene periods and improving the accuracy of sediment dating to refine the intercorrelation of Arctic peat samples and cores.

5. Glacial-geologic mapping of former ice sheets in both the Arctic and Antarctic to clarify the dynamic behavior of the ice sheets and their changes with time, with special attention to distinguishing between marine and terrestrial components, ice shelves, and ice streams and to exploring the general parallelism of variations of the ice sheets in the two hemispheres thought to exist during the Quaternary.

POLAR REGIONS AND FUTURE ENVIRONMENTAL CONCERNS

Looking to the future, the polar regions are perceived as uniquely vulnerable to climatic changes of the kind projected to occur in the coming century as a result of atmospheric increases of CO_2 and other "greenhouse gases." In a matter of decades in the future, significant decreases may develop in the extent of snow cover on the continents and of sea ice on the polar and subpolar seas, with a range of societal impacts favorable and otherwise.

In the longer run, however, our principal concern is with the fate of the polar ice sheets, because, to the extent that they do not displace ocean water, changes in their size affect sea levels. Changes of sea level, if sufficiently rapid, would have enormous social and economic impacts on densely populated coastal areas throughout the world. Sea levels have risen and fallen many times in the past, sometimes by 100 m or more, as a result of changes in glaciation. Yet, little can be said with confidence about the rates of change of sea level that are possible when polar ice sheets are affected by climatic changes of the kind anticipated in the centuries ahead.

Major ice sheets are dynamic entities potentially capable of a variety of behavioral responses to a changing climate. Marine-based ice sheets, among them the West Antarctic Ice Sheet, are considered the most vulnerable to a future warming of climate. In West Antarctica, higher ocean temperatures and a loss of protective sea ice are thought capable of lessening or entirely removing the restraints now acting on the ice shelves and thereby speeding up the ice discharge from the main ice sheet. However, a contrary view, supported by the most advanced model simulations to date, is that the ice sheet may be relatively immune to the climatic warming and maintain a slow growth as the bedrock beneath it continues to rebound from its ice age depression. In these conflicting circumstances it is clear that questions concerning the rapidity of ice-sheet changes, the rate of change of global sea-level that may result, and the further effects of a climatic warming on other ice masses in both polar regions all require further study by means of a judicious blend of modeling analysis and field studies. In these connections we identify two principal focuses for future research:

- o The response of snow and sea ice to climatic change

and

- o The dynamics of ice sheets.

In regard to snow and sea ice, we recommend:

1. Collection of data on short-term (1-10 years) and long-term (10^2-10^3 years) variations in extent of ice in relation to climatic changes, the long-term data to be derived largely from proxy climatic indices, including ocean-floor sediment cores.
2. Synoptic case studies to clarify the interactions among the atmosphere, snow cover, and sea ice, employing microwave and other satellite imagery as well as measurements from oceanic and ice-based data buoys.
3. Modeling experiments to explore the range of possible effects on sea ice of climatic changes resulting from increasing levels of CO_2 and other radiatively active atmospheric pollutants.

In regard to dynamics of ice sheets, we recommend:

1. Improved models of terrestrial and marine-based ice sheets and their incorporation into general climate-system models.
2. Construction of scenarios of the atmospheric conditions over the Antarctic and Greenland Ice Sheets at various stages of a climatic change such as that predicted to result from increased atmospheric CO_2.
3. Studies of heat transfer at the bases of all large ice shelves by modeling the subglacial water circulation in the manner that it has already been modeled for the Ross Ice Shelf.
4. Assembly of evidence from a variety of sources to determine whether the West Antarctic Ice Sheet was

present or absent during the last interglacial (about 120,000 years ago) and its status at various times prior to and following that interglacial.

Field data on ice sheets will be needed, together with data on trends in surface air temperature and global sea level. These data should include ice-sheet thickness, surface and bed slope, surface mass balance, basal mass balance, internal structure, ice velocity, and iceberg calving and melting rates. Many of the data could best be obtained by remote sensing from a dedicated polar-orbiting satellite; however, a field program would also be required to complement this effort.

World Climate and the Polar Connection:
An Introductory Perspective

The Earth's climate has varied substantially in the past. The polar regions have shared in these variations, often to a greater extent than lower-latitude regions. The geologic record shows that during roughly nine-tenths of the past 500 million years there was little or no permanent ice and snow anywhere on this planet. At those times, the Earth as a whole was considerably warmer than it is today. During the other one-tenth of the time, ice has been present in the higher latitudes of one or both hemispheres, sometimes in amounts several times greater than those of the present Antarctic and Greenland ice sheets. During such ice-age conditions, most lower-latitude regions have also cooled significantly, as have the oceans.

The Earth has been locked in the grip of an ice age (the Quaternary) for about the last 2 million years. However, since its inception there have been wide fluctuations in volume of ice, temperature, and other climatic conditions between glacial and interglacial stages, at intervals of tens of thousands of years. Today, we are poised atop an uncommonly warm interglacial of uncertain future duration, the beneficiary of a respite from the much deeper chill that is more typical of an ice age.

Within the present interglacial, lesser climatic fluctuations have been documented. Among these have been so-called "little ice age" events, at intervals of 2000 or 3000 years, characterized by enlarged mountain glaciers, an expanded Arctic ice pack, and a generally cooler, stormier climate in some parts of the world. In addition to the little ice ages, a whole range of more rapid, mostly irregular fluctuations has continually been sweeping the planet and doubtlessly will continue to do so in the future.

The causes of these fluctuations of widely differing time scale and character are far from understood. Strong evidence exists for a role of slow Earth-orbital changes in pacing the arrival and retreat of the major ice-age glacials and interglacials. Natural variations of atmospheric composition may be involved on a range of time scales of change. Intrinsic variability of the sun, changes of atmospheric transparency caused by violent volcanic eruptions, and perhaps other natural environmental disturbances may contribute to the more rapid changes of climate.

Yet there are reasons to believe that much of the variability of climate is internally generated by inherent and chronic imbalances among the atmosphere, the oceans, and the ice and snow masses of our planet. Each of these domains is typically in a state of dynamic unrest and communicates that unrest in various ways and on various scales of time to the other domains of what is collectively referred to as the "climate system."

In addition to the atmosphere, the oceans, and the cryosphere (ice and snow), the climate system also includes the land surface and the biosphere (here defined as vegetation and other organic matter in direct or indirect contact with the atmosphere). The disparity in time scales of unrest of these several domains of the system is reflected in the characteristic time required for each to adjust to a change imposed by the others interacting with it. This response time ranges from a week or two for the atmosphere to about a year for sea ice to a range of times from centuries to tens of millennia for the continental ice masses. The response time of the ocean depends on whether we are referring to the upper mixed layer (around 100 m in depth), which reacts on a time scale of 10 years or so, to the cold fresh intermediate waters with a life cycle of decades, or to the deep waters whose cycling time for mixing with the surface waters may exceed 500 years.

To quantify adequately all the principal physical, chemical, and biological processes that contribute to climatic variability and change is both an urgent need and a formidable challenge. It requires the development of comprehensive theoretical models of the climate system that are capable of simulating its complex time-dependent behavior. So far, only in limited respects has that time-dependent behavior been modeled well enough to have clear interpretive or predictive value. In the past decade, however, appreciable advances have been made in the realism of climate models and in our understanding of the ways in which the climate system responds to changes in "external" conditions, that is, conditions that influence the system from beyond its boundaries.

Among the potentially variable external influences of greatest importance to climate is the sun, which provides virtually all of the thermal energy to drive the oceanic and atmospheric circulations. It is estimated that a 1 percent change in total solar radiation, if sustained over a period of many years, would result in a change in global mean surface temperature of about 1.5°C. This calculation takes into account what we believe are the most important interactions within the climate system. The total radiation from the sun, the so-called "solar constant," changes by a few tenths of 1 percent over intervals of days or weeks, as demonstrated recently by sensitive satellite measurements. Indirect evidence suggests that, in at least some respects, solar radiation also changes on longer time scales associated with one or more of the well-recognized rhythms of solar activity (those of about 11, 22, and 80 years, perhaps others of even longer duration).

Another kind of alteration of radiation from the sun comes from slow changes in the shape of the Earth's orbit about the sun and in the direction of its spin axis relative to the plane of orbit (the ecliptic). Although these orbital changes have only a minor influence on the total incoming solar radiation (insolation) received by the whole planet in a full year, they can cause as much as a 12 percent change in the insolation received at a particular latitude in a particular month. The Serbian astronomer Milutin Milankovitch was the first to work out the geometry of this effect and to show that it could result in cyclical changes of climate over periods of about 20,000, 40,000, and 100,000 years. The Milankovitch theory has recently received considerable attention as a result of findings that, in the past million years of paleoclimatic data sufficient to show it, both global-average temperature and ice volume have tended to vary in cycles of precisely these periods and to have maintained a uniform phase relationship with the orbital changes.

Although the Milankovitch mechanism seems to operate most strongly in the northern hemisphere, the climatic changes related to it have been more or less parallel in both hemispheres. Over sufficiently long periods, changes of global sea level, induced by changes in the volume of the continental ice sheets in the northern hemisphere, are now seen as a likely mechanism to link the two polar regions and to result in parallel changes of ice in the Antarctic.

Large volcanic eruptions in the past have injected both ash particles and sulfur dioxide into the stratosphere. All but the smallest of the particles would have fallen out within days or weeks; the rest would have remained suspended long enough to be carried intercontinental distances by atmospheric winds. The sulfur dioxide would have been converted to submicrometer-size sulfate particles whose residence time at the high altitudes involved can be as much as 2 or 3 years. Both the fine ash and the sulfate particles are likely to have caused a temporary cooling of the surface climate by intercepting a fraction of the solar radiation that would otherwise pass through to the surface. A cooling effect of a fraction of $1^{\circ}C$ in hemisphere-wide average temperature has been identified following each of several major eruptions in the past century. A record of these and earlier eruptions has been preserved in ice cores from the Greenland and Antarctic Ice Sheets, appearing as thin layers of high sulfate content at various depths in the ice.

In the present century another externally induced change has been introduced into the climate system in the form of a buildup of atmospheric carbon dioxide (CO_2). Since the nineteenth century vast stores of carbon have been burned as fossil fuels (principally coal, petroleum, and natural gas). Roughly half of the CO_2 produced in this way appears to have stayed in the atmosphere; the other half, apparently, has been taken up by the oceans. Changes in the mass of the biosphere, especially the forests, may also have contributed to shifts in atmospheric CO_2 levels. The aggregate increase in atmospheric CO_2 levels since the late nineteenth century is now approaching 20 percent; the rate of increase has been about 0.5 percent each year recently.

The influence of increasing CO_2 on climate has been studied extensively in the past decade. This gas absorbs and redirects earthward some of the infrared heat emission from the Earth's surface and lower atmosphere that would otherwise escape more directly to space. A similar radiation-trapping role is played by water vapor, by clouds, and by various trace gases copiously released to the atmosphere by human activities, among them methane, nitrous oxide, and chlorofluorocarbons. The net effect of the added CO_2 and of these other infrared-absorbing gases is to warm the surface by a process commonly (if imprecisely) referred to as the greenhouse effect. Based on a number of independent studies using climate models of various degrees of sophistication, a doubling of atmospheric CO_2 concentration from 300 to 600 parts per million by volume (ppmv) would be likely to result in a worldwide average rise in equilibrium surface temperature of approximately 2 to 3°C. The warming would probably be enhanced in the polar regions, perhaps by as much as a factor of 3 in the Arctic.

Anticipated future increases of atmospheric CO_2 content are such that a doubling by some time in the twenty-first century is a reasonable expectation. The time required for an increase of such magnitude, and the climatic warming expected to result from it, depends on a number of uncertain factors, among them the future rate of uptake of CO_2 by the oceans, the thermal inertia of the oceans, the role of the biosphere in exchanging additional carbon with the atmosphere, and, most of all, the future rate of consumption of fossil fuels. If historically typical past growth rates of worldwide consumption of fossil fuels continue, a doubling of CO_2 could be expected by around the middle of the next century. If, on the other hand, the relatively slow growth of energy demand in the past few years is more representative of future trends in fossil-fuel consumption, then the time of CO_2 doubling could be delayed by several decades to around the end of the twenty-first century. Uncertainties about many details of the cycling of carbon between the atmosphere, oceans, and biosphere add an important caveat to these projections. In any case, it seems likely that by the end of this century the CO_2 warming will have become evident as such in the meteorological record and within a matter of decades thereafter will have begun to transform the climate to levels of warmth unprecedented in human experience. The CO_2 warming is likely to be augmented by the similar effects of other infrared-absorbing trace gases also expected to continue accumulating in the atmosphere.

From measurements of the CO_2 trapped in old ice brought up in cores from Greenland and the Antarctic, it appears that the atmospheric concentrations of this trace gas have been fairly constant for many thousands of years prior to the modern industrial era. However, measurements on ice dating back to the last glaciation, about 20,000 years ago, indicate that atmospheric CO_2 levels were then only about 60 percent of present levels. Such a CO_2 deficit was almost certainly a result of glaciation and not a cause of it. Yet it could have contributed to the perpetuation of a glacial climatic state once established by other environmental influences.

The implications of the anticipated future global warming effect of CO_2 are many; these will unfold at different rates and with diverse consequences to human society. Probably of greatest long-term significance, however, are the potential effect of such warming on the integrity of the polar ice masses and related concerns about the stability of worldwide sea levels. It is principally in these connections that we focus on the polar regions as a concern for the future.

The Polar Regions as a Source of Climatic Unrest

Both the documented history of the Earth's climate and the theory of climate as developed through climate models indicate that the polar regions are highly sensitive to variations of climate. Further, the polar regions apparently play a major role in the physical processes that animate the global climate system into a state of continual fluctuation, a role now considered virtually certain on the time scale of the glacial-interglacial succession of the present ice age. Further still, the polar regions may be a prime mover of global climatic fluctuations on one or more time scales in the range from years to tens of millennia commensurate with the widely differing response times of polar ice and snow.

To determine the full extent of involvement of polar processes in the behavior and causation of global climatic fluctuations will require improved understanding of the climate system as a whole. A quantitative grasp of the longer-term interactions taking place among the Earth's oceans, ice masses, and atmosphere will be necessary; currently all of our insights and observations are adequate to discern these interactions only in vague outline.

ROLES OF THE TWO POLAR REGIONS IN CLIMATE: PARALLELS AND CONTRASTS

Patterns of global climate are largely determined by the global system of atmospheric winds and oceanic currents. The winds, in turn, are a response to the unequal heating of the Earth and atmosphere by the sun, especially to the contrast in heating between the tropics and the polar regions. The oceans are driven into large-scale motion partly by the stress of atmospheric winds on their surface and partly by patterns of heat and moisture exchange with the atmosphere that affect water density. Air and ocean water are the two working fluids of a planetary-scale thermodynamic engine that share the burden of moving heat in each hemisphere out of the tropics toward the polar regions, where it is ultimately radiated back to space.

The inequalities of heating that fuel the global climate engine depend in a complex way on geography and season; they also vary irregularly with time. The tropics contribute to these heating variations mainly through changes in the distribution of precipitation, cloudiness, and surface temperature of the ocean. The polar regions contribute to them mainly through changes in net heat loss associated with changes in atmospheric boundary-layer structure, in the extent of highly reflective snow fields, and in the extent of sea ice, which strongly regulates the fluxes of heat, moisture, and momentum between the atmosphere and the ocean water below.

Looking more closely at the mechanisms by which the polar regions may apply leverage to the throttle of the global climate engine, we discover some stark differences between the Arctic and Antarctic. These differences can be traced to major physiographic contrasts, which, together with some of their immediate consequences for global climate, are summarized in Table 1.

POLAR ENERGY-TRANSFER PROCESSES

Factors largely determined by sea-ice conditions and seasonal snow cover dominate the energy balance of the Arctic Basin. A layer of sea ice (about 3 m), coupled with a highly stable density structure of the ocean surface layers beneath, insulates the vast energy reservoir of the Arctic Ocean from the atmosphere. Each summer the long hours of sunlight, aided by a relatively sudden lowering of albedo associated with snow melt and the formation of puddles on the ice, melts the ice at rates in excess of 1 cm per day. Small changes in the summer radiation budget can have large effects on the ice; conversely, interannual variations in cloudiness and in the timing of snow melt and puddling exert great leverage on the radiation budget. In all seasons, wind

TABLE 1 Contrasting Characteristics of the Two Polar Regions Relevant to Global Climate

Characteristic	Arctic	Antarctic
Physiography	Ocean nearly surrounded by	Continent surrounded by ocean
	Ice covered ocean (at sea level)	High-altitude ice sheet (up to 4.2 km) surrounded by seasonal sea ice
	Ice-sheet area 2×10^6 km^2 (Greenland)	Ice-sheet area 13×10^6 km^2 augmented by another 20×10^6 km^2 of sea ice in winter
Dominant factor in energy balance	Sea-surface energy budget	Radiant heat loss from atmosphere and surface
Dominant mechanism of heat and mass exchange with lower latitudes		
Atmosphere	Migratory weather systems as in lower latitudes	Gravity-flow (katabatic) winds off ice sheet balanced by upper-level inflow interacting with strong circumpolar westerlies
Ocean	Currents through a few shallow channels (mainly one connecting to Greenland and Norwegian seas)	Shallow and deep-water transport across open boundaries interacting with strong circumpolar current

and water stresses on the ice cause it to part, opening leads that in winter release large bursts of ocean heat to the air before they are quickly filmed over by thin new ice. The result is an ice matrix of widely varying thickness, each element of which has its own characteristic temperature and heat balance. Further changes in heat balance arise from the occurrence in summer of extensive layers of low stratus clouds above the ice.

The energy balance of the Antarctic continent is contrastingly dominated by a combination of rapid radiative heat losses to space through the clear and dry atmosphere above the ice sheet and a net solar heating much smaller than that in the Arctic owing to the large size and high albedo of the ice sheet together with a lesser absorption of solar radiation by the thinner overlying atmosphere. The absorption of solar radiation in the surrounding oceans is strongly modulated by large seasonal and interannual variations in the extent of sea ice there. The intense cooling over the interior of the ice sheet creates reservoirs of extremely cold and dense air. This air readily flows with a down-slope component toward the ocean in all sectors of the continent and gives rise to the strong katabatic winds that figure prominently in the unique character of Antarctic climate. The massive outflow of air associated with these drainage winds results in an inflow of air at higher altitudes that participates in the strong radiative cooling over the continent and maintains the Antarctic as an efficient planetary heat sink.

The katabatic winds of Antarctica play other roles in energy and mass transfer between ice, air, and ocean water that are not yet quantitatively understood. The winds lift a considerable mass of snow from the ice sheet and transport it, together with its latent heat, into the ocean; this process is not, however, believed to have a major effect on the long-term mass balance of the ice sheet. The winds also produce open-water polynyas through which a considerable share of sea-air transfer of heat and moisture occurs and otherwise affect the manner in which the ocean surface is able to freeze. (It happens that the most persistent polynyas are located adjacent to glacier tongues fed by ice streams within the ice sheet; the draw-down of ice by the ice streams creates channels that allow the winds to gather exceptional force in such locations.) In addition, the winds may regulate the rate of formation of cold Antarctic bottom water near the continent, primarily in the Weddell Sea. These various wind effects allow the circum-Antarctic ocean to exchange heat with the atmosphere much more actively than the Arctic Ocean, which by contrast is covered with ice all year, highly stable in its upper layers, and severely restricted by geography in its ability to exchange water with lower-latitude ocean basins.

POLAR EFFECTS ON GLOBAL CLIMATE FLUCTUATIONS

Polar Feedback Mechanisms

In the course of a climatic fluctuation or change, of whatever origin, certain global energy and mass-transfer mechanisms within the climate system can adjust in ways that tend either to amplify or to damp the original climatic perturbation. These are commonly referred to as positive or negative feedback mechanisms, respectively.

A positive feedback mechanism that operates in both polar regions to amplify a climatic change involves a relationship between polar albedo and temperature. Except during the polar night, any process that acts to increase the area of polar snow and ice, with its high albedo (reflectivity) relative to that of ocean or land, results in an increased loss of heat by reflection of solar radiation back to space. Consequently, less heat is available to warm the atmosphere and to melt the snow, leading to a further increase in the area of snow and ice. A process that decreases the area of polar snow and ice leads to the opposite result. The net effect of this feedback is to increase the sensitivity of polar climate to a perturbation of the overall climate system. Virtually all climate models, from the most elementary to the most advanced, take this feedback into account.

Related albedo effects, not so easy to incorporate into models, involve the breakdown of the crystalline structure of snow and the formation of melt ponds on sea ice, particularly with the arrival of thawing temperatures in spring. In both cases considerable reductions of snow and ice albedo may occur, mainly in the near-infrared region of the solar spectrum not sensed by the human eye. These albedo effects may lead to accelerated thawing and to further consequences for the polar heat budget and for the evolution of snow and ice conditions in later seasons of the year.

A second positive feedback mechanism that affects the polar regions involves water vapor. Like CO_2, water vapor is a good absorber of infrared radiation. An increase in temperature will generally result in a larger atmospheric water-vapor content, which, through the greenhouse effect, further increases the temperature. Conversely, decreases in temperature reduce atmospheric water vapor, thus further decreasing temperature. This process, which operates most effectively in the higher latitudes, is also taken into account in virtually all climate models. Neglecting it results in a gross under-estimate of the sensitivity of the climate system to factors that affect atmospheric heating rates.

Both of these feedback mechanisms operate somewhat differently in the Arctic than in the Antarctic. The albedo-temperature mechanism is enhanced in the northern hemisphere because snow cover on land responds to temperature more quickly than does sea ice, and there is much more land in the northern hemisphere. In the southern hemisphere the vast expanse of ocean is more resistant to changes in surface temperature. For this reason, it is believed that the astronomical theory of climatic change (on the millennial time scale of the Milankovitch mechanism) must operate more effectively in the northern hemisphere, where a relatively small change of insolation at high latitudes in the late summer can produce a relatively large change in albedo and temperature.

The water-vapor feedback mechanism is also probably more effective in the Arctic because there is more atmospheric water vapor over the Arctic Basin, at its sea-level elevation, than over the central Antarctic, at its high altitude, where the atmosphere overhead is not only more rarified but maintained at low humidities by subsidence caused by the katabatic outflow near the surface. It should be emphasized in this connection that even the best current climate models do not realistically treat the wind flow over the Antarctic, a limitation of models that warrants special attention in other connections as well.

A third feedback mechanism, long considered to be predominatly negative but not necessarily so under all conditions, concerns the effect of changes of cloudiness on the planetary heat budget. In daytime and during the summer season, the dominant effect of an increase of cloudiness is to increase the planetary albedo, thus contributing to a cooling of climate. However, at night or during the winter season, the dominant effect of an increase of cloudiness is to insulate the lower atmosphere from strong radiative heat losses to space, contributing to a warming of climate. The net effect of increased cloudiness in polar latitudes would therefore tend to favor warming in winter and cooling in summer. A factor tending to cause increased (stratus) cloudiness in polar ocean areas is the moisture added to the atmosphere by exposed ocean water when sea ice breaks up in summer, a situation likely to cool the surface and to slow the rate of further ice breakup in that season. On a more global scale, it remains to be verified that the planetary average cloud cover may change, as, for example, in response to a warming effect of CO_2; modeling studies so far carried out to investigate this possibility have indicated that such global-scale cloudiness changes may be small.

Other feedback mechanisms involving the polar regions are more subtle and even less well understood. One of these involves the occasional tendency of higher- and mid-latitude weather systems, which ordinarily move from west to east, to become stationary in "blocking patterns." When they occur, such patterns may be so persistent that cold polar air masses are enabled to flow toward the equator along the same pathways for weeks at a time. This situation occurred, for example, during the unusually cold winters of 1976-1977 and 1977-1978 in the eastern United States. Presumably, blocking patterns develop and break down in direct or indirect response to changing requirements for global heat or momentum exchange between different latitude zones of the Earth. In any case, they can be viewed as another potent feedback mechanism by which the polar regions are linked to the development and evolution of global-scale climatic fluctuations.

Sea Ice and Climate

The largest variations in the intensity of the polar heat sinks are associated with variations of ice extent on the ocean. As already noted, sea ice powerfully regulates the rate of heat and moisture exchange between air and sea. It has been estimated that the removal of all floating ice in the Arctic Ocean would result in a total annual heat flow from the ocean to the atmosphere five or six times greater than what it is now. It has also been estimated that the removal of the highly reflective ice would lead to a doubling of the amount of solar heat absorbed by the Arctic Ocean in summer. These results make clear that variations in sea ice can have a potentially enormous influence on air-sea heat exchange.

In the northern hemisphere, the maximum extent of sea ice (usually in March) is about 5.5 percent of the total area of the hemisphere; the minimum extent (usually in August) is about 3 percent. In the southern hemisphere, the maximum extent of sea ice (in September) is about 8 percent of the area of the hemisphere, whereas the minimum (in March) is only about 1 percent. Thus, the annual variation of sea-ice cover has at least four times as much leverage on total air-sea heat exchange in the Antarctic as it has in the Arctic.

Interannual variations of sea ice may likewise be larger in the Antarctic, but direct evidence to confirm this supposition is limited to the satellite era. During the global climatic warming that occurred in the first half of this century the area of the Arctic Ocean covered by sea ice is estimated to have decreased by roughly 10 to 15 percent, or less than 1 percent of the total area of the hemisphere. A shrinking ice cover enhances the role of the ocean in poleward heat transport, thereby reducing poleward temperature contrasts and slowing the global atmospheric circulation. Such a slowing was a feature of the northern hemispheric circulation during the Arctic warming between the decades of 1910 and 1930.

The timing and extent of both seasonal and interannual changes of sea ice may affect climate in another manner as well. At times when the polar seas are relatively ice free, the large heat capacity of the water adds considerable thermal inertia to the polar atmosphere and thereby tends to lengthen the dominant time scales of climatic variability. Conversely, at times when the polar seas are ice covered, the ice insulates the atmosphere from such thermal inertia effects hence the climate system responds differently.

Beginning about 10 years ago, satellite imagery gave us the ability to monitor both seasonal and long-term variations of sea ice on a global basis and in unprecedented detail. In addition to imagery in visible and infrared wavelengths, which is subject to obscuration by clouds, imagery by means of scanning microwave radiometers is now available that not only "sees" the ice through clouds but can distinguish between new (seasonal) and old (multiyear) ice. In addition this imagery provides a means to track the location and behavior of open-water polynias throughout the year. This powerful satellite capability promises rapid future gains in our understanding of sea-ice dynamics and of air-sea-ice interactions important to global climate.

Polar Modulation of the Oceans

The oceans owe much of their character to the polar regions. The bulk of the deep water in the Atlantic, Pacific, and Indian Oceans accumulated there from sources around the Antarctic continent and in the North Atlantic. This bottom water is continually being renewed; the time required to replace all of it is estimated at between 500 and 1000 years. The displaced bottom water eventually regains contact with the atmosphere. The character of ocean bottom water and the processes by which it is formed are believed to have differed considerably from those of today in geologic eras prior to the Quaternary. The reason for this can be traced to tectonically related changes of continental configuration and interocean connections.

Both polar regions are sites of intense sea-air heat exchange, which is believed to initiate the main process through which the world ocean contributes to the balancing of the global energy cycle. Because of the long time required to transport ocean heat over the vast distances involved, variations in the rate of heat loss to the polar atmosphere, which result from the natural variability of the atmosphere and its interaction with sea ice, have ample opportunity to interfere with the balancing process, thus setting in motion fluctuations of global climate on time scales as varied as years, decades, and centuries.

In general, the most intense heat exchange between the atmosphere and ocean occurs in limited regions of the world where extremely cold polar air masses first contact the unfrozen ocean surface. These regions include the northwest corners of the Pacific and Atlantic Oceans, the Norwegian Sea, and the Southern Ocean around Antarctica. The enormous quantities of heat extracted from the ocean in these regions aggregate to a large share of the total planetary heat transport by the ocean as a whole.

In each region of such intense air-sea heat exchange, cold water masses are created that sink to intermediate depths in the ocean and migrate slowly into low latitudes. There they eventually resurface, cooling and otherwise modifying the tropical atmosphere. On a global scale, this process of water-mass formation promotes not only a large-scale heat transport within each ocean basin but also a net interbasin transfer of heat between the North Atlantic and the tropical Pacific. This transfer is achieved by ocean currents that carry the chilled water into the South Atlantic, then eastward in the circum-Antarctic current to the Pacific, where it is balanced by a net surface heat gain at lower latitudes. Such interbasin ocean coupling strongly reinforces our perception that to explain and predict longer-term climatic fluctuations we need a better quantitative understanding of global ocean behavior and of the polar air-sea-ice interactions that contribute to such behavior.

Snow Cover and Climate

Snow cover on land is clearly a result of transient weather and climate conditions. But snow may have causal roles in climatic change beyond those already noted in connection with polar feedback mechanisms. The contribution of polar snow to raising the solar reflectivity (albedo) of the Earth is well known, yet this is not the only leverage of snow on climate. The excellent insulating properties of polar snow fields allow snow surface temperatures to drop more or less independently of the temperatures beneath. This drop in temperature, in turn, can result in a large reduction of the overall radiative heat loss in high latitudes, with important consequences for global climate.

Other climatic effects of snow cover include altering the net heating effects of aerosols present in the polar atmosphere, delaying spring warming by absorption of latent energy in the process of ripening and melting and altering the stability of the lower atmosphere that affects the form and extent of polar cloudiness in spring and summer. More subtle effects of snow cover may extend to an influence on regional atmospheric circulation patterns.

Ice Sheets and Climate

The major ice sheets of Greenland and Antarctica, as well as many lesser ice caps in high latitudes, owe their existence to favorable conditions of temperature, precipitation, and other qualities of both climate and geography maintained over long periods of time. Changes in volume and extent of such ice bodies occur in response to long-term climatic changes. Net changes of mass of all the world's ice bodies contribute to changes in the volume of water in the oceans. To the extent that ice bodies do not displace ocean water their mass changes contribute to changes of sea level. If sufficiently large, changes in sea level not only would have an impact on human society in obvious ways but would tend to alter the geography of the world and the depth of the interbasin ocean passages that affect the pattern and strength of global ocean circulations.

The rate and ultimate magnitude of changes in the major ice sheets that might follow from future climatic changes are uncertain. In view of the special importance of this subject, it is addressed in more detail in a later section of this report.

RESEARCH NEEDS: THE POLAR REGIONS AND CLIMATE DYNAMICS

Two principal focuses for research effort are needed. First, models of the global climate system should be developed in which special attention is devoted to climatic processes in the polar regions. Second, a better understanding is required of the global-scale response of the oceans to atmospheric changes in polar and subpolar latitudes.

With regard to modeling requirements:

Efforts are needed to improve the manner in which various polar processes are simulated in current climate system models. Among these processes are the following:

- The response of sea ice to atmospheric and oceanic changes;
- The atmospheric effects of snow cover and sea ice, as well as those of other surface characteristics such as vegetation and soil moisture, and their changes;
- The effects of cloudiness on the heat budget of the surface and atmosphere and its changes;
- Air-sea interactions in the polar regions and their relation to ice conditions; and

o Ice-sheet dynamics and the response of ice sheets to atmospheric and oceanic changes.

The katabatic winds over the Antarctic should be given high-priority attention in global climate models. Although neglected in current models, these drainage winds profoundly influence the surface heat budget over the region, including that of the surrounding ocean, and indirectly modulate the behavior of Antarctica as a planetary heat sink. The tendency for these winds to be concentrated along ice-stream channels, and to form persistent open-water polynyas where these channels meet the ocean, should be studied as a mechanism of long-term air-sea-ice interaction.

Processes of blowing snow raised by the katabatic winds and of sublimation, should be further examined as agencies of potentially significant mass and energy transport both across the boundaries of ice sheets and between their various parts.

Climate models should be developed that are capable of simulating each of two forms of solid precipitation over the ice sheets: snowfall originating from high-latitude storm systems and ice-crystal deposition ("diamond dust") that occurs most commonly under clear-sky conditions. This capability would be especially valuable in models designed to assess the mass balance of ice sheets past and present and long-term ice-sheet behavior.

Understanding of atmospheric blocking patterns and their variations in frequency of occurrence should be a major goal of climate research. As a fundamental mode of atmospheric circulation, blocking plays an important role in regulating heat transport into and out of the polar regions including the advection of cold polar air masses to mid-latitudes in winter. An ability to predict the onset and termination of blocking patterns would lead directly to more skillful long-range weather forecasting in many areas of the world.

Conditions favoring the coexistence of a glaciated Antarctic and a seasonally ice-free Arctic (excepting the Greenland Ice Sheet), and the implications for the climate of lower latitudes, should be studied with appropriately designed climate models. Such extreme polar asymmetry, although believed not to have existed at any time in the past 3 million years, may develop in the future according to modeling studies that suggest that the Arctic ice pack may be capable eventually of disappearing for at least part of the year in response to a future climatic warming anticipated from increasing atmospheric CO_2 levels. Further insights into this matter could follow from efforts to reconstruct the climate of the late Tertiary, from about 13 million to 3 million years ago, during which a similar situation is thought to have prevailed.

With regard to the oceanic response to changes in forcing by the polar atmosphere:

Identification of the ocean response to changes of polar atmospheric conditions, and clarification of the processes involved, should be pursued by means of suitable field studies and modeling strategies. Among the least adequately understood processes that govern the ocean response, which should be the principal target of this effort, are processes related to the surface heat and moisture exchanges around Antarctica, including those related to sea ice, and to the subsequent ocean transport of heat storage anomalies to lower latitudes.

Variations in the production and transport of intermediate and bottom ocean-water masses should be explored as a potential source of persistent sea-surface temperature anomalies in lower latitudes and of related long-term global climatic fluctuations. Intermediate and bottom water masses that occupy a large part of the world ocean are formed in the subpolar regions of both hemispheres, at interannually varying rates, and exchanged slowly (on the scale of decades and centuries, respectively) among various ocean basins and with the surface water. To an extent as yet unclear, these water mass exchanges may be capable of altering sea-surface temperature fields in the lower latitudes, and thus of altering global-scale climate, over periods of decades and centuries. This possibility should be explored by

- o Analyses of the record of sea-surface temperatures;
- o Chemical and radioisotope measurements that trace the history and trajectories of water masses; and
- o Improving ocean models capable of simulating the movements and transformations of water masses.

The Polar Regions as Windows on the Past

Paleoclimatologists have made great strides in the past two decades in deciphering the record of past climates stored in sediments of the ocean floor, in ice sheets, and in the tundra and boreal zones of the far north. As the diverse pieces of this record have been extracted and compared, using a variety of new experimental and statistical techniques, our understanding of the history of the Earth's climate has dramatically broadened. This understanding, in turn, has shed new light on the physical behavior of the climate system, on the causal mechanisms of climatic change, and on the range of possibilities for future change.

Rather than with the results of polar paleoclimatic studies per se, we are concerned here with identifying the diverse polar media from which information about past climates can be extracted, the techniques used to extract such information, and opportunities for further advances in understanding the record of past climates, with special emphasis on the polar regions.

Progress in reconstructing past climatic changes not only provides insights into past behavior and potential future behavior of climate but also aids in validating models used to assess the physical mechanisms of climatic change. Models can be tested by determining how well they simulate the geographical and seasonal distributions of global climate; indeed, the best of models do rather well in this respect. But that does not guarantee that the models will also simulate a transition to some different past or future climate. Paleoclimatic reconstructions provide us with an opportunity to test the models in new arenas, to determine how well they capture the essence of the physical processes involved in climatic change, and to address the problem of predicting future climate with confidence.

POLAR SOURCES OF INFORMATION ABOUT PAST CLIMATES

Various natural media in the polar regions have contributed to our knowledge of past climates and their variations over a wide range of time scales. The five principal media include the following:

- Ocean-floor sediments: Core samples of such sediments have now been extracted in nearly every part of the world's ocean basins, including the polar oceans. These give the longest continous record of global environmental conditions, extending several hundred million years back in time with a resolution of the order of 1000 years. The relative distributions and isotopic composition of microfossils at various depths in such cores are the main indicators of past conditions in the ocean, which in turn reflect past climates.
- Ice sheets: Ice cores contain a record of the accumulations of snow, sometimes resolvable as individual annual layers as far back as 10,000 years or more. Isotopic analysis of such cores not only assists in the identification of the annual layers as such but allows reconstruction of the variations of both snow accumulation rates and atmospheric temperature at the time the snow fell. Locked in the ice are samples of the atmospheric gases and aerosol particles that were deposited with the snow. Thus ice cores provide a wide range of information about past climate variations and related environmental events, with the potential for tracing these as far back as hundreds of thousands of years.
- Lake bottoms and bogs in the Arctic and sub-arctic: The relative abundances of pollen and spores in lake bottoms and bogs in Arctic tundra and boreal regions show the types of vegetation that existed when each layer was deposited, in some cases resolvable as annual deposits. From this information, the climates that supported past ecosystems can be deduced. In the Antarctic, however, there are few places where this method of reconstructing past climates can be applied because of an insufficient abundance and diversity of pollen grains there.
- Trees. Trees growing in subpolar areas contribute information about variations of climate during the past

few centuries, revealed by variations in their annual growth rings. In high latitudes, the annual growth of indigenous conifers and deciduous species is confined to the relatively short summer growing season; ring variations reflect primarily temperature conditions in that season.

o Polar ground: The ground in polar regions can exhibit a variety of distinctive features or surface patterns that are caused by the action of ground ice in permafrost. Other features are related to advances and retreats of glaciers; these provide information about past glacial mass-balance changes, and hence about climatic variations occurring at the time. The temperature distribution with depth in the ground is capable of revealing temperature trends over the past century or longer.

In the following sections we indicate the kinds of information about the past that are contained in these natural polar media and the means by which this information can be extracted.

OCEAN-FLOOR SEDIMENTS

Some 10,000 sediment cores, extracted from the ocean floor in widely scattered areas of the world, lie in refrigerated storage in U.S. repositories. To decipher the paleoclimatic record that they contain, it is essential first to be able to infer the age of each layer of core in which climatic changes have left distinctive signatures. Four general types of methods are used to estimate that age:

o Detection (in sufficiently long cores) of reversals of the magnetic field of the Earth that are recorded simultaneously in bottom sediments around the world. The last clearly identifiable magnetic reversal was about 730,000 years ago. The ages of younger core layers are then interpolated by assuming constant sedimentation rates between that time and the present.

o Application of radioisotopic dating procedures: Carbon-14 can be used in dating core layers back about 20,000 years. The radioactive uranium series can be used for older layers, back more than 100,000 years. Potassium/argon dating can be used for layers dating back to the last reversal of the magnetic field and beyond. In combination with these procedures, further refinement of age determinations is possible by scaling to the Milankovitch cycles. In this way, the chronology of deep-sea cores can be established with a potential accuracy of a few thousand years through the last million years in spite of changes of sedimentation rate likely to have occurred during that interval.

o Detection of changes in the ratio of the stable isotopes of oxygen ($^{18}O/^{16}O$) in calcareous bottom-dwelling microfossils. This ratio reflects the isotopic composition of the seawater from which the micro-organisms built up their shells while alive. The sea-water ratio, in turn, varies nearly in parallel throughout the oceans, in response to change in the size of the ice sheets. Because the isotopes in the water mix completely within about 1000 years, cores considerable distances apart, even those in different ocean basins, can be cross-dated and all such cores linked to a master chronology.

o Detection of sequences of change in microfossil assemblages common to those in other (longer) cores from the same region of the ocean that are able to be dated by other means.

A principal objective of analysis of ocean-floor sediments is the estimation of past changes of ice-sheet volume and world sea levels. In the process of evaporation of ocean water, fractionation occurs between molecules of water containing ^{18}O and ^{16}O, in favor of the lighter and much more abundant isotope attaining the vapor phase. Therefore, snow deposited on the ice sheets is relatively deficient in ^{18}O. During periods of ice sheet growth, the oceans accumulate excess ^{18}O relative to ^{16}O; during ice sheet decay, the opposite is true. These changes in the isotopic composition of ocean water are incorporated into the calcitic shells of bottom-dwelling micro-organisms living at the time. As the remains of succeeding generations of these organisms are buried in the bottom sediments, the time variations of the globally aggregated volume of ice are reflected in the sediments, albeit with some imprecision because not all ice sheets have identical ^{18}O composition. These variations translate directly to information about ocean volume, a fact that has been corroborated in two ways: by studies of datable marine terraces on tectonically stable or uplifted island coasts and by mapping of terminal moraines of glaciers and ice sheets to estimate ice volume directly. Although problems of interpretation remain, such independent sources of information are now converging to a consistent picture of the succession of changes of both ice volume and sea level during the past several glacial cycles.

A second principal objective of analysis of ocean sediments is estimation of positions of water masses and of temperature fields at the sea surface. The geographical distribution of surface-dwelling microfossil assemblages in sediments deposited at a given time in the past typically shows coherent patterns similar in form to, but somewhat displaced from, modern-day patterns. Such distribution patterns have a consistent relationship to the position of major current systems, ocean water masses, and sea-surface temperature fields.

Estimation of past extent of sea ice, a third objective of analysis of ocean sediments, is on a less quantitative footing than estimation of sea-surface temperatures. A number of lines of evidence, however, are consistent with the presence of substantially increased sea-ice cover in both hemispheres during the last glacial maximum about 18,000 years ago. This conclusion is based mainly on studies of microfossil assemblages in which it is recognized that primary productivity of micro-organisms is inhibited by permanent sea ice. Primary productivity determines the kinds of organisms that can exist in the presence of sea ice and the rate at which their remains accumulate in the sediments. Additional information about ice extent comes from determinations of the distribution, thickness, and equatorial limit of ice-rafted terrestrial material, notably volcanic ash, deposited on the ocean floor when and where the ice melts.

GLACIAL ICE

Cores extracted from the ice sheets of Greenland and the Antarctic and from certain lesser Arctic island ice caps contain a high-resolution record of climatic change in past centuries and millennia. The important initial step of dating the layers of an ice core, to establish the absolute chronology of the climate record it contains, is approached where possible by discerning each year's contribution to the snow (or ice-crystal) accumulation. In some cases annual layers can be resolved as such by stable-isotopic analysis and other means as far back as about 10,000 years before present. Dating of still older ice layers is less precise and depends on radioisotope dating (e.g., ^{14}C, ^{10}Be, ^{36}Cl, ^{85}Kr), on modeling of the dynamics of the ice mass, or on correlations of features in the core with independently datable environmental events having a likely causal connection with such features (for example, sulfate-enriched ice layers correlated with known volcanic eruptions).

For several reasons related to information content of the ice, to logistic factors, and to differences in drilling technique involved, ice cores are divided into three general categories according to depth of penetration, as shown in Table 2.

TABLE 2. Categories of Ice Cores

Category	Depth	Time Span[a], Resolution[a]
Shallow	To 150 m	100 to 5,000 years; annual layers clearly identifiable
Intermediate	To 600-900 m	1,000 to 30,000 years; annual layers may be identifiable up to 10,000 years
Deep (to bedrock)	To greater than 1 km	Possibly 10^6 years in Greenland, and 2-3 x 10^6 years in Antarctica; resolution and dating precision degrade rapidly on approach to bedrock

[a]Depends on snow accumulation rate.

On a high polar ice sheet or glacier where little or no summer melting occurs, the new snowfall (or ice-crystal precipitation) each year buries all older snow (firn). The underlying layers are compacted by the added weight. Eventually, the firn is transformed by the increasing overburden pressure into glacial ice; the intercrystalline air spaces or pores are closed off into bubbles, preserving samples of the atmosphere and its gaseous composition at the time and level the snow was deposited. Everything else that was deposited with the snow or as dry fallout--organic and inorganic material, soluble and insoluble particles--is also preserved with little or no degradation for many thousands of years.

Much information about past climates and about environmental conditions related to climate can be gleaned from ice cores by analysis of a wide range of physical characteristics of the ice and its laminations and of the chemical composition of the ice, foreign substances, and trapped gases. Analysis of any pollen grains and other organic material present in the ice also contributes to knowledge. Measurement of the bulk dielectric properties of the ice is useful for interpretation of internal reflections of radio waves as observed with airborne scanners that reveal subtle inhomogeneities in the interior of ice sheets over wide areas. Each of these diverse measurements gives different but complementary information about past climates, some of it resolvable on an annual--even seasonal--basis.

Isotope Chronology

Stable isotopes have become the basis of sensitive new analytical techniques in glacial stratigraphic analysis. The ratio of two such isotopes, ^{18}O and ^{16}O, has been mentioned in connection with ocean-sediment cores. In the case of snow or ice-crystal precipitation accumulating on an ice sheet, this ratio is directly influenced by the temperature at which the precipitation particles are formed in the atmosphere. (The ratio is more positive when the temperature is higher.) Each year the $^{18}O/^{16}O$ ratio of the snow varies between summer and winter, providing a sensitive technique for counting years. In some areas with high rates of snow accumulation, this technique can be used to obtain well-dated chronologies back as far as 10,000 years or more. The $^{18}O/^{16}O$ ratio also reveals the longer-term changes in temperature in the atmosphere at levels of snow formation and the relationship of snow accumulation rates to temperature. These data, in turn, allow comparisons between climatic changes in the northern and southern hemispheres and correlations between temperatures and such causally related factors as ash and sulfur output from volcanic eruptions, also recorded in the ice.

There are about ten different radioisotopes found in measurable amounts in ice cores. Some are associated with the water molecules (mainly deuterium and tritium);

others, with the entrapped air (mainly ^{14}C); and still others, with particles or dissolved foreign matter (a variety of isotopic species). Fallout of several shorter-lived radioisotopes from atomic tests conducted since World War II show clearly in the upper firn layers; these, together with natural tritium and ^{210}Pb, can be used as aids in dating ice samples back 30 or more years. In older layers several longer-lived radioisotopes can be used for dating back about 1,500 years. Beyond that, ^{14}C offers the only reliable radioactive dating of ice at present (back about 20,000 years), although there are other radioactive species that are potentially available for dating in this same age range and even beyond.

Measurements of ^{14}C variations with depth in ice cores that are precisely datable by other means have additional climate-related value. Such measurements provide a means of calibrating the radiocarbon "clock" beyond the limit of about 8,000 years achievable from tree-ring analysis. Moreover, the ^{14}C variations themselves, which arise from changes in the flux of cosmic radiation at the Earth caused by changes of the magnetic field of the sun, are a measure of longer-term variations of solar activity that have been implicated as a cause of climatic changes on Earth.

Chemical Signals in the Ice

The original chemical composition of new-fallen snow or ice crystals is preserved essentially without change in ice as old as 120,000 years. The remoteness of most polar ice masses from sources of natural and anthropogenic aerosols means that the trace chemical impurities found in the ice tend to reflect regional or global-scale atmospheric burdens of those substances whether of marine, terrestrial, or extraterrestrial origin. Chemical analysis of ice cores is a promising way to investigate historical variations of the background atmospheric content of trace gases and particles and to assess the contribution of human activities to them.

New developments in the chemical analysis of polar ice, potentially important in unraveling the causes of climatic changes, include the following:

- Identification of ice layers containing enhanced concentrations of sulfate ions and various trace species consistent with a volcanic source and verification of a volcanic source by cross-dating with known eruptions. This procedure may allow the reconstruction of a detailed chronology of historical volcanic activity not otherwise possible and lead to a more reliable assessment of the contribution of volcanic eruptions to past climatic changes.
- Identification of variations of nitrate ion concentrations in Antarctic firn during the past century and evidence of their correlation with variations of solar activity on the time scale of the 11-year sunspot cycle. This correlation, which remains to be independently verified, may enable the reconstruction of variations in solar activity extending back at least 10,000 years.
- Determination from ice cores that the concentration of CO_2 in the atmosphere was only about 60 percent of its present value during the last glacial maximum about 20,000 years ago. The same analytical technique may be capable of providing a more detailed chronology of CO_2 variations during and since the last ice age.

POLLEN IN THE TUNDRA AND BOREAL ZONES

Analysis of pollen grain speciation in natural sedimentary deposits of the higher latitudes, primarily lake bottoms and bogs but also glacial ice, is the realm of palynology. Pollen analysis is a major source of information about variations of climate in the Arctic and sub-Arctic, particularly in the postglacial period. On the other hand, it is of much more limited applicability in the Antarctic because of the rarity of organic deposits there that contain a useful diversity of pollen species.

Both tundra and forest zones of the Arctic are populated by many varieties of plants. Over the course of a summer any recessed surface in those zones will tend to collect a deposit on the order of 20 to 100 different pollen species. Much of this "pollen rain" is of local origin, but some may be imported by winds from considerable distances away. Over the years the accumulation of pollen-bearing sediments in lakes and bogs, on rare occasions recognizable as annual deposits, provides a record of the local pollen rain and any variations in speciation that reflect longer-term changes in the ecosystem.

Because the complexion of both tundra and boreal vegetation is related to contemporary climate (primarily to summer temperature and secondarily to precipitation), variations of pollen speciation with depth in cores extracted from high-latitude deposits, plotted in "pollen diagrams," are an index of climatic variations.

As with ocean sediments and ice cores, dating of the pollen core layers is a crucial step. Here, ^{14}C dating procedures are usually well adapted to the organic composition and the typical age range of the deposits and allow accurate dating back about 25,000 years. However, problems can arise because the deposits are sometimes disturbed by the mechanical action of ground ice or contaminated by younger carbon in plant rootlets that have penetrated from above. In the case of lake beds, ice scouring of the banks can cause influx of "old" terrestrial vegetation into the bottom sediments. In some Arctic regions, the rate of accumulation of organic material in the sediments is so slow that substantial thicknesses of core, spanning a wide range of ages, are required to provide sufficient carbon for each date determination.

Pollen diagrams from the northern polar regions are available from Alaska, Canada, Greenland, Spitsbergen, and the Soviet Union. Together, these might make possible a detailed reconstruction of historical and postglacial climatic changes and their geographic patterns over the Arctic as a whole. The conversion of information about time variations of pollen speciation to information about variations of climate, based on multivariate statistical-transfer-function techniques, is a success story no less significant than the application of similar techniques to the climatic interpretation of changes in microfossil assemblages in deep-sea sediments and more recently to the interpretation of tree-ring variations over wide areas in the lower latitudes. In most tundra areas, however, full realization of the potential of this procedure is inhibited by the lack of taxonomic pollen keys that extend to the species level. Such a level of discrimination in pollen identification has been pioneered in Greenland. The reliable estimation of relative pollen populations usually requires the individual identification of at least 100 pollen grains at any given level in a sediment core.

TREE RINGS

The great boreal forests of the north circumpolar regions, populated mainly by evergreen conifers but often intermixed with a variety of hardy deciduous species, extend northward to fairly well-defined Arctic tree lines in both North America and Eurasia. Relatively isolated stands of such trees are found also in more polar latitudes, for example, in the Brooks Range in Alaska. These trees, like those in alpine areas at lower latitudes, add new growth each year only during the short summer growing season and with a vigor that varies from year to year depending primarily on variations of local air temperature, snow conditions, and insolation. The changes in growth are reflected in the varying widths and other characteristics of the new wood added each year, evident in cores extracted from their trunks by increment boring tools to reveal the sequence of annual growth rings over the lifetime of each tree. By a judicious combination of measurements of such rings from many trees of the same species in an area, in some cases including measurements on fallen dead wood that tends to be well preserved in the dry polar cold, precisely dated tree-ring indices extending back through several centuries can be developed for some polar regions. Multivariate statistical techniques can then be applied to these indices, using recent weather records for calibration, to extract information about the interannual variations and longer-term changes of temperature and precipitation in the Arctic.

POLAR GROUND PHENOMENA

A ubiquitous form of ice in the polar regions is ground ice, present in the perennially frozen ice-soil matrix in areas where ground temperatures tend to remain below 0°C (defined as permafrost). Together with glaciers, ground ice can sculpt the polar landscape, leaving telltale signs of past climatic conditions. Glaciers, however, can later advance over some of these creations and obliterate them.

In permafrost, which has a relatively low thermal conductivity and large specific heat, the distribution of temperature with depth below the surface reflects mean annual ground-surface temperature conditions in former times. For example, a study of the temperature profile in a deep permafrost borehole near Point Barrow, Alaska, indicates that the mean annual ground-surface temperature has warmed about 4°C since 1850, about half the increase having occurred since 1930. The distribution of permafrost in deeper layers below ground in many regions of the Arctic and sub-Arctic is not in accord with that expected under conditions of equilibrium with present climate; rather, it is a vestige of the ice age.

Pingos—conical ice-cored mounds that range from 20 to 400 m in diameter and up to 70 m in height--are striking features of Arctic and sub-Arctic terrain. They are formed when massive layers of ground ice grow near the surface of permafrost. When mean annual air temperatures at the time of formation are lower than about -5°C, pingos have a different structure from those formed at higher mean annual air temperatures. In areas where the climate has since become warmer and the ice melted, the remains of pingos, or pingo scars, give an indication of past permafrost conditions and the range of mean annual air temperatures that prevailed.

Ice wedges, another feature of permafrost terrain, are formed when water freezes in cracks opened by contraction in the permafrost and the freezing process is repeated over a period of many years. These wedge-shaped ice masses can appear as vertical or inclined dikes frequently exceeding 1 m in width and as much as 10 m in depth below the surface. Ice wedges grow only in permafrost and are particularly well formed when the mean annual air temperatures are lower than about -5°C. Ice wedges are part of a three-dimensional polygonal network of ice, visible as "polygonal ground" in many tundra areas.

When permafrost thaws as a result of a prolonged warming trend and leads to melting of the ice wedges, the cavities left by the wedges may fill with sediments. Such ice wedge "casts" are widespread in the sub-arctic and are remnants of the Wisconsin ice age in areas when mean annual temperatures were -5°C or lower.

A land form indicative of former snow-line altitude, and mean annual air temperatures of about -10°C, is the cryoplanation terrace. Such terraces are large bedrock steps on ridges or hilltops, developed gradually over long periods by erosional effects of frost action and meltwater flow along the margins of perennial snow fields.

Taken together, these and other geomorphic features peculiar to the polar regions are valuable clues to past climates and their changes on a variety of time scales, notwithstanding problems of accurate dating of the times of their formation.

In addition to the processes in frozen ground, there are deposits of soil, gravel, or boulders attributable to the scouring action of glaciers. Glacial deposits yield a variety of information of indirect value in reconstructing past climates, including the areal distribution of glacial ice at specific times in the past, the fluctuations of glacier termini through time, and the former altitudes of the snow line on mountain glaciers where accretion of snow is balanced by ablation (evaporation plus melting).

The reconstruction of past climatic changes from such information is not always unambiguous because different combinations of changes of seasonal temperature and precipitation can result in similar glacial responses. Yet, this kind of effort provides much valuable insight into the history of climate during both glacial and postglacial times, especially when coupled with modeling studies of glacier dynamics. Of special interest is the use of such information to determine more exactly the extent of past continental ice sheets in North America and Europe, from which the climatic conditions that prevailed at various stages of the sequence of Quaternary glaciations can be inferred.

RESEARCH NEEDS: THE POLAR REGIONS AND PAST CLIMATES

Several parallel research efforts are needed to exploit more fully the great potential of polar sedimentary deposits to establish the chronology of past climatic variations and to clarify the environmental processes responsible for such variations.

<u>Available ocean-bottom cores should be more intensively analyzed</u>, with special attention to

- Developing and applying techniques to determine past distributions of sea ice and their fluctuations (especially by analysis of biogenic remains and ice-rafted detritus recovered in the cores) and
- Refining time-control techniques to make possible improved absolute dating and interhemispheric correlations of climatic events.

<u>Longer, high-deposition-rate cores of ocean-floor sediments in high-latitude areas should be collected</u>,

taking advantage of newly available hydraulic piston coring technology, for the purpose of

- Improving the time resolution of climatic variations reflected in sediments and
- Extending the period of record of past climates.

A vigorous program to acquire and analyze polar ice cores should be maintained over the next decade, with focus on

- Developing fast-operating, lightweight ice-core drilling devices for both shallow and intermediate-depth coring, as well as more fully exploiting existing deep-drilling technology, and
- Pursuing a geographically broadened ice-coring program in both polar areas, with a suitable balance between shallow, intermediate, and deep cores, backed by a strong laboratory core-analysis program in which a wide range of measurements can be made in support of a variety of climate-related objectives.

An intensified program of pollen analysis of sediments in tundra and boreal regions should be supported as a source of information on the climatic history of the higher latitudes, particularly the Arctic and sub-Arctic, with the principal aims of

- Improving understanding of the geographic distribution of present-day pollen rain in Arctic and sub-Arctic areas, as required for the interpretation of past pollen changes revealed by lake and bog sediment analyses in high-latitude regions and of their connection with climatic variations;
- Collecting a larger number of long lake-sediment cores at strategic sites throughout the northern polar regions as a means of providing a clearer, more geographically detailed history of vegetation and climate in both the Holocene and pre-Holocene periods; and
- Improving the accuracy of dating of the large number of Arctic peat samples and cores already collected, as needed to refine correlations of time horizons among different samples and to facilitate prompt evaluation of newly collected samples.

High-quality glacial-geologic mapping of former ice sheets in both the Arctic and Antarctic is needed to clarify the dynamic behavior of the ice sheets and their changes with time, with special reference to

- Distinguishing between marine and terrestrial components, ice shelves, and ice streams (imbedded glaciers) and
- Investigating the extent to which variations of the ice sheets have been parallel in the two hemispheres during the Quaternary, which would presumably involve a linking effect of global sea-level changes.

The Polar Regions: A Concern for the Future

The polar regions influence global-scale climatic changes, which, in turn, influence the polar regions. Sea ice, glaciers, ice sheets, and the amount of snow on land are all affected. Here, we emphasize the situation with regard to the major ice sheets, the main concern being that changes in size of ice sheets can affect worldwide sea level. Future changes of sea level, if sufficiently rapid, would displace the many densely populated communities situated along the coasts of the world, at potentially enormous social cost. Sea levels have risen and fallen many times in the past, sometimes by 100 m or more, from such a cause. Little is known, however, about the rates of change of sea level that are possible when polar ice sheets are disturbed by climatic changes of the sort that may occur in the decades and centuries ahead.

RESPONSES OF GLACIERS AND ICE SHEETS

The world's ice masses, from the smallest alpine glaciers to the great ice sheets of Antarctica and Greenland, are dynamic entities. They can assume any of a variety of modes of behavior. There are basically four such behavioral modes:

- o Stable steady state, in which the ice mass remains essentially unchanging in size or shape unless there is a change in some external environmental condition.
- o Cyclic steady state, in which the size and shape of the ice mass change in a periodic or quasi-periodic way, entirely as a result of internal causes. When averaged over a time that is long compared with its

natural period, the properties of this ice system can resemble those of a stable system.

o Unstable steady state, in which the size and shape of the ice mass remain unchanged as long as environmental conditions remain unchanged, but the response to even a temporary environmental change is irreversible. If the original environmental conditions are restored, the ice mass will not necessarily return to its original size and shape.

o Transient state, in which a change in the size and shape of the ice mass occurs without any change of environmental conditions. Generally, though not necessarily, this change involves a transition from one kind of steady state to another.

At a certain stage of the behavior of an ice mass in cyclic steady state, the lower portion of the ice mass may be in relatively rapid motion (e.g., advancing), with a thinning of the upper portion, a condition referred to as surging. As many as 10 percent of all valley glaciers surge at more or less periodic intervals. Such behavior might also be a property of major ice-sheet drainage basins, but this possibility remains to be verified.

The response of an ice sheet or glacier to a climatic change depends to an important extent on whether it is a terrestrial body of ice, mainly resting on land that is above sea level (as are most Arctic and alpine glaciers, the bulk of the Greenland Ice Sheet, and most of the East Antarctic Ice Sheet) or whether it is a marine body of ice, mainly grounded below sea level (as is most of the West Antarctic Ice Sheet). Marine ice sheets are likely to show the greater, and the more rapid, adjustment in total ice volume to a change of climate or sea level.

Ice sheets that flow into the ocean may develop floating ice shelves that extend some distance from the part that is grounded. Examples are the Ross and Filchner-Ronne Ice Shelves of West Antarctica. The presence or absence of an ice shelf is considered likely to have an important bearing on the response of the main ice sheet to changes in climatic forcing.

Terrestrial Ice Sheets

Ice is plastic and can slowly deform and creep. Most ice sheets flow away from one or more high central regions. In the past decade, glaciologists have contributed much to the understanding of the shapes, flow patterns, and other properties of such ice sheets.

Many kinds of models of ice-sheet behavior have been developed in efforts to duplicate the three-dimensional, nonsteady-state, nonlinear flow of real ice sheets. One group of models (so-called "zero-balance models") is useful for clarifying many aspects of ice-sheet flow and can be readily transformed into a time-dependent mode to predict how an ice sheet might respond to changing climate. Among the kinds of models that lend themselves to such predictions are two-dimensional time-dependent models that treat an ice sheet as if it were an assemblage of ice columns resting on bedrock of a specified topography. In these models, however, such essential properties as vertical gradients in stress, velocity, or temperature must be parameterized; the same holds true for any mechanism of sliding over the underlying bedrock. Another type of time-dependent models, known as flowline models, is in some respects the most promising of all. In this type, ice flow is modeled in terms of two-dimensional sections along a flow trajectory, fully incorporating gradients in vertical planes but requiring parameterization for processes acting transverse to the flow. Basal sliding can be incorporated using several possible sliding mechanisms. Experiments with flowline models have been successful in simulating observed glacier surges, and also surgelike behavior in a large ice sheet through the use of a hypothetical "friction lubrication" mechanism that is presumed to govern basal sliding. Such a mechanism has been confirmed as physically valid by laboratory experiment, but its significance for actual glaciers and ice sheets cannot be decided without a fuller understanding of their overall basal water balance. It should also be emphasized that surging is not yet known to be a characteristic of any part of the Antarctic or Greenland Ice Sheets.

Marine Ice Sheets

A number of theoretical two-dimensional models of marine ice sheets (those grounded below sea level) show that such ice sheets can be either stable or inherently unstable, depending on the depth and shape of the bed on which they rest. This behavior suggests that a rise in sea level could lift the marginal portions of a marine ice sheet sufficiently for them to become part of the adjacent floating ice shelves. The presence or absence of underwater sills near the margin of a marine ice sheet, such as those existing in the Ross and Weddell Seas that adjoin West Antarctica, is a critical factor in determining whether the ice sheet will be stable or unstable for a given sea level.

Ice streams are a feature of both marine and terrestrial ice sheets that may play a crucial role in ice-sheet response. The term refers to fast-flowing currents of ice within the body of an ice sheet, bounded by much slower-moving ice. Models incorporating ice streams in realistic detail are still in an early stage of development. Ultimately ice-sheet models must be able not only to generate their own ice streams but also to relate movement of the ice-sheet grounding line, particularly in the ice streams, to such factors as downdraw of the ice stream drainage basins and the behavior of any fringing ice shelves.

A few studies with three-dimensional models have been made of the response of marine ice sheets to a rise in sea level, such as the rise that began shortly after the last glacial maximum, about 16,000 years ago. Some of these studies tend to confirm that a marine ice sheet depends for its survival on the ice shelves that surround it. Thus, the vulnerability of such an ice sheet to climatic warming would depend on the vulnerability of its ice shelves. If so, and if rising temperatures in the air and the surrounding seawater were to lead to the disappearance of ice shelves, then rapid shrinking of the marine ice sheet would follow. However, opinions are widely divergent on the speed with which such ice shelves as those of West Antarctica would respond to temperature changes. Moreover, the most advanced model studies carried out so far suggest a much less pivotal role for the ice shelves.

Ice-sheet instabilities of one kind or another are an inherent ingredient of many of the modeling concepts discussed in this report. Models based on such concepts cannot suffice to verify whether actual ice sheets possess such instabilities, but comparisons between modeled and actual ice-sheet features can provide valuable clues as to their reality. In any case, the models are valuable as testbeds for evaluating proposed instability mechanisms and their consistency with known past and present ice-sheet behavior.

EVIDENCE FOR PAST CHANGES

The record of the interplay of past changes in the extent of sea ice, in the volume of land ice, and in climate might provide possible analogs of future events. As indicated earlier in this report, the most likely outcome of human activities (e.g., burning of fossil fuels) is a climatic warming. The state of the cryosphere during past intervals that were warmer than the present one is, therefore, of particular interest.

Sea Ice

Variations of the extent of sea ice during the past several million years can be inferred to some extent from analysis of ocean-sediment cores. By this means it can be surmised that during the last glacial maximum, about 18,000 years ago, sea ice in the North Atlantic extended far south of its present winter maximum extent near 50° N in the vicinity of Newfoundland. In the Arctic Ocean there is good evidence for the uninterrupted presence of sea ice during the last 700,000 years, and possibly during a much longer period.

In the Antarctic, the sedimentary record suggests that during the last glaciation (between 100,000 and 15,000 years ago) the sea ice in the Southern Ocean extended substantially farther north than at present, particularly in summer.

Ice Sheets

Changes in the global-total volume of ice on land affect the $^{18}O/^{16}O$ ratio in ocean water, as noted earlier in this report. These changes are preserved in the shells of benthic microfossils in ocean-sediment cores. The observed changes of the $^{18}O/^{16}O$ ratio in ocean sediments have been interpreted to indicate that a large ice sheet, probably that of East Antarctica, accumulated between about 15 million and 13 million years ago and remained in being thereafter. Other studies, however, imply that this ice accumulation may have occurred at an earlier time. The ice-volume change corresponds to a difference of about 65 m in sea level.

The West Antarctic Ice Sheet may have had a very different history. By one interpretation, because the land mass there is mostly below sea level the ice sheet must have formed initially from ice shelves growing out of a coalescence of floating tongues of outlet glaciers of the East Antarctic Ice Sheet, as well as from glaciers flowing out of the central and coastal mountains of West Antarctica. Extensive ice shelves probably could not have formed until summer temperatures at sea level were near or below freezing. The ice sheet could subsequently have shrunk during prolonged episodes of warming climate in which summer temperatures at sea level reached about 5°C above their present levels and above the freezing point along the ice-shelf margins. Unlike the East Antarctic Ice Sheet, it might temporarily have disappeared altogether during exceptionally warm intervals, then have redeveloped by the same means as its initial formation.

The Greenland Ice Sheet, like the East Antarctic Ice Sheet, in part rests on bedrock below sea level but is mainly terrestrial (based on land near or above sea level). Although smaller than the West Antarctic Ice Sheet, its melting would produce about the same rise in sea level (roughly 6 m), because less of it displaces ocean water. Little is known about the past history of the Greenland Ice Sheet; when it first formed and how much it diminished in size during subsequent warm intervals are not clear. The southwest part receded about 100 km during the Hypsithermal warm period of the Holocene, between about 9500 and 5000 years ago. During the past 4800 years, it has fluctuated only a few kilometers around its present position.

The North American Laurentide Ice Sheet, which no longer exists, offers an interesting perspective on ice-sheet behavior from the past. Reconstructions of the situation that existed about 8,500 years ago suggest that the central portion of that great ice sheet, in the area of Hudson Bay, was rapidly drawn down by ice streams to a saddle-shaped remnant, after which it took only 200 years to disappear. In certain respects an analogy can be drawn between this apparently abrupt demise of the North American Laurentide Ice Sheet and possible future events in West Antarctica, but it cannot be pushed too far in view of some fundamentally different circumstances involved in the two cases.

Climate of the Last Interglacial

The last interglacial period (called the Sangamon or Eemian age) began about 125,000 years ago and lasted no more than about 15,000 years. On the basis of recent studies, conditions in both the atmosphere and the oceans at the time were quite similar to those of the present interglacial. Evidence from raised shorelines ("strandlines"), however, points to higher sea level at that time and, by implication, to a smaller total volume of ice sheets in the world. Sea level on coasts thought to be more or less stable tectonically were from 2 to 8 m higher than at present, but the difference might be attributable to geoid changes. The stable isotope ratios of oxygen in the ocean changed in a way that is consistent with such a rise in sea level. The additional water in the ocean is about what would have been added by melting of either the West Antarctic or Greenland Ice Sheet but could have been contributed by partial melting of more than one ice sheet.

If the West Antarctic Ice Sheet should have been absent for a few thousand years during the warmest part of the last interglacial, the most likely reason is that sea levels in the Antarctic, in keeping with the warmer climate of the time, had risen too high for the Ice Sheet to survive except on the highest bedrock of the region. Perhaps the disappearance of fringing ice shelves preceded that of the main ice sheet. It has been suggested that the West Antarctic Ice Sheet is being actively drawn down today by two ice streams in the Amundsen Sea sector (the Pine Island and Thwaites glaciers), but this is not confirmed by recent estimates of their drainage basin mass balance. An alternative projection is that the West Antarctic Ice Sheet is near its minimum postglacial size today and will expand as the bedrock continues to recover from its glacial depression.

CURRENT STATUS AND TRENDS

Sea Ice

In the Southern Ocean surrounding Antarctica, the maximum area of sea ice in late winter (September) is about eight times greater than at its minimum in late summer (March). In the Arctic, the ratio resulting from seasonal change is only 2 to 1, and the distribution of land makes the extension of area of sea ice in winter longitudinally asymmetric; for example, in the Sea of Okhotsk and the Labrador Sea it can extend to 50° N, but in the Norwegian-Barents Sea, open water persists in winter north of 75° N.

A substantial amount of multiyear ice occurs in the Arctic Ocean. Direct freezing results in a thickness of only about 3 m; when compressed into pressure ridges, the thickness can increase greatly. In the Antarctic, other than in the Weddell Sea, most sea ice is first-year ice, probably less than 2 m thick.

Ice Sheets

Little is known about the mass balance of the Greenland Ice Sheet, for annual iceberg discharge and meltwater runoff have not yet been reliably determined. There is some observational and modeling evidence that it may be slowly growing on the western side of the central ice divide and slowly shrinking on the eastern side, but the average rate of change in volume of the ice sheet as a whole is unlikely to exceed one part in 10^4 per year. With the possible exception of the Jacobshavn Glacier, which flows into Disco Bay and which has rapidly retreated in the last century at the same time that surrounding ice has built up, dramatic changes do not appear to be occurring there.

The East Antarctic Ice Sheet is by far the largest in the world. It is based mostly above sea level. Estimates of the change in volume in its interior ice-drainage systems suggest a growth equivalent to a drop in sea level of about 1 mm per year; yet, sea level in the past century has actually been rising at nearly this same rate. Less is known about volume changes in the marginal drainage systems of the East Antarctic Ice Sheet; of those few that have been measured, some margins show buildup, others depletion. As in Greenland, the ice volume as a whole must be changing only slowly—at most by one part in 10^5 per year. Because some parts of this ice sheet are based below sea level, the kind of instability characteristic of marine ice sheets could exist along their ocean fronts.

The present mass balance of the West Antarctic Ice Sheet is also unknown, although there is much concern about it in view of the unstable behavior of which deep-bedded marine ice sheets are thought capable. Evidence concerning the past behavior of the grounded ice-sheet margin is conflicting; some evidence points to a retreat in the past 17,000 years from a position near the edge of the continental shelf, but other evidence from the sedimentary record of the Ross Sea can be interpreted as showing a much lesser extension of the ice sheet there during the past 20,000 years.

The evidence concerning current changes in the West Antarctic Ice Sheet is also ambiguous, making it difficult to draw any firm conclusions about what is happening there. Attempts to model the behavior of the ice sheet suggest either that it is in an oscillatory regime, with the ice sheet in a postsurge state, or that it is in a steady-state fast-flow regime.

In its extreme form, the prediction of drastic shrinkage of the West Antarctic Ice Sheet would result in a rise in sea level of about 5 m in as short a time as 200 years. However, this extreme view conflicts with the fact that sea level has been rising an order of magnitude more slowly than the rate implied by such a drastic shrinkage. Whether the ice sheet is currently poised in an unstable steady state is an open question. Both theoretical modeling and field work continue in an effort to clarify this point.

CLIMATE AND POLAR ICE: FUTURE PROSPECTS

The present interglacial period began about 10,000 years ago, possibly a bit earlier. Of the several previous interglacials for which the chronology of climate has been reconstructed in some detail, none appears to have endured longer than 10,000 to 15,000 years. Therefore, we might assume that global climate should soon begin to move into another full glacial period. In fact, such a transition may already have begun with the end of the Hypsithermal warm period some 5000 years ago. The astronomical (Milankovitch) theory suggests that the next full glacial age should arrive about 6000 to 8000 years from now.

The next few _hundred_ years present a quite different picture. On that time scale, the warming associated with future increases of atmospheric CO_2 and other "greenhouse" gases resulting from human activity will be likely to dominate any ice-age cooling trend. Indeed, this factor may prevail over most other climate-disturbing factors as well and result in a net warming beginning some time in the next several decades. This warming probably would be amplified in the polar regions. Toward the middle of the twenty-first century the net warming could aggregate to at least $1^{\circ}C$ in the global average and to several degrees in the Arctic though probably not in the Antarctic. Further net warming would be likely to follow in later decades despite transient cooling episodes attributable to volcanic activity or to the natural variability of climate of other origins.

Massive climatic warming would have obvious implications for snow and ice. The thickness and extent of sea ice would be diminished in both hemispheres. Models indicate that with a polar warming of somewhat less than 5°C, the Arctic Ocean could become ice free in summer, although not in winter. Plausibly, this condition could occur by the middle or latter part of the next century. In the Antarctic, that extent of warming could diminish by half the minimum sea-ice extent in summer as well as produce surface meltwater on the larger ice shelves.

Mountain glaciers in sufficiently cold climates might temporarily advance because of increased snowfall, as may already be happening in parts of the Canadian Arctic and in Antarctica. In the longer term, however, mountain glaciers nearly everywhere would shrink in the face of a general climatic warming.

The Greenland Ice Sheet would either shrink, expand, or be essentially unaffected, depending on the net changes in mass balance resulting from increased snowfall over its interior and increased melting and ablation at its edges.

The East Antarctic Ice Sheet would probably be little affected until the warming had been in progress for a long time, as it is likely to respond more slowly than the other large ice sheets. Portions that are grounded below sea level, however, could behave differently from the main body of the ice sheet.

The West Antarctic Ice Sheet would probably be little affected unless or until its ice shelves, exposed to higher ocean temperatures and less protected by sea ice, were to be lifted off their pinning points, as might already have happened recently in the Amundsen Sea sector. What would occur next is a matter of controversy. This marine ice sheet might rapidly drain down in a few centuries, in which case a rise in sea level of about 5 m would follow, or it might change little and even to some extent advance over the next millennium.

It must be emphasized that a drastic and relatively rapid response of the West Antarctic Ice Sheet to a general climatic warming of the kind projected to occur in the several decades ahead cannot be ruled out at this stage of our knowledge. The inherently unstable nature of a marine ice sheet in response to climatic change is such that, once the response begins, it could be irreversible.

RESEARCH NEEDS: THE POLAR REGIONS AND FUTURE CLIMATE

Two principal focuses for a research effort are paramount: the response of snow and sea ice to climatic change and the dynamics of ice sheets.

With regard to the relationship of snow and sea ice to climatic change:

Data are needed on the short-term (1-10 years) and long-term (10^2-10^3 years) variations in extent of ice in relation to changing climatic conditions. Direct observations of sea ice can provide data for short-term studies, but information on the long-term variations will come largely from proxy climatic sources, including ocean-floor sediment cores.

Synoptic case studies should be made to clarify the interactions between the atmosphere, snow cover, and sea ice. Microwave and other satellite imagery are needed for this purpose, as well as atmospheric measurements from oceanic and ice-based data buoys.

Modeling experiments are needed to explore the range of possible effects on sea ice of climatic change resulting from increasing CO_2 and other radiatively active atmospheric pollutants. This effort will require the development of improved models of sea ice, based on results of such projects as the Arctic Ice Dynamics Joint Experiment (AIDJEX) and the Marginal Ice Zone Experiment (MIZEX), together with other empirical information on ice motions, distribution, and thickness; it will also require improved understanding of ocean circulations and their effects on sea ice.

With regard to the dynamics of ice sheets:

Improved models of both terrestrial and marine-based ice sheets should be developed. This effort could benefit from analog arguments involving surging glaciers. Varying the key parameters in ice-sheet models would help to reveal the dynamic responses of ice sheets under different conditions. Ice-sheet models should eventually be coupled with models of the atmosphere and ocean.

Scenarios should be constructed of the atmospheric conditions over the Antarctic and Greenland Ice Sheets at various stages of a climatic change such as that .

associated with increasing CO_2 to support the development of models of ice-sheet behavior. For example, it would be useful to examine atmospheric conditions with a persistent 0°C summer temperature over a broad coastal belt of the Antarctic Ice Sheet. As already noted, the katabatic winds above the surface of an ice sheet should receive special attention in atmospheric models because of their effect on the heat balance of the Antarctic.

The heat transfer at the bases of all the large ice shelves should be studied by modeling the subglacial water circulation in the manner it has already been modeled for the Ross Ice Shelf.

Evidence from a variety of sources should be marshaled to establish whether the West Antarctic Ice Sheet was present or absent during the last interglacial and what its status was at various times prior to and following that interglacial. This information could provide much needed insight into the present situation and into the likely response of the ice sheet to a future warming induced by CO_2.

Field data on the ice sheets are needed along with data to define trends in surface air temperature and global sea level. These data should include ice-sheet thickness, surface and bed slope, surface mass balance, basal mass balance, internal structure, ice velocity, and iceberg calving and melting rates. Many of the data can best be obtained by remote sensing from a dedicated polar-orbiting satellite, particularly one capable also of monitoring surface elevation changes. However, even with the finest of remote-sensing capabilities, a vigorous field program will be required.

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Polar Research—A Strategy

In 1980, the Polar Research Board initiated a series of studies to develop a strategy for polar research over the next decade. The last such survey had been published in 1970. Rather than a single volume covering the entire field, the Board decided on a series of reports on various disciplines of polar science or particular problems related to polar research. The principal objectives are to review the status of research, to identify promising directions for future effort, and to recommend priorities in research. The reports also deal with the facilities and support required to realize the recommended research objectives. To date, the following reports in this series have been issued:

An Evaluation of Antarctic Marine Ecosystem Research, 1981

Study of the Upper Atmosphere and Near-Earth Space in Polar Regions: Scientific Status and Recommendations for Future Directions, 1982

Polar Biomedical Research - An Assessment, 1982 and Appendix: Polar Medicine - A Literature Review, 1982

Snow and Ice Research. An Assessment, 1983

Permafrost Research: An Assessment of Future Needs, 1983

The Polar Regions and Climatic Change, 1984