8 August 1980, Volume 209, Number 4457 SCIENCE

Focus on Polar Research

A. L. Washburn

Polar research in the sense of modern science as opposed to exploration came of age with the International Geophysical Year (IGY) 1957–1958 [biology was not included as a formal IGY program (*1*)]. Greatly expanded knowledge of the polar regions was obtained from the IGY. Investigators also came to recognize how little they really knew about this subject. A useful review of the state of knowledge was published a decade ago (*2*). Despite all the subsequent advances, many key challenges remain today, some old, some new, and some with dramatic implications for the future. In this article, I focus on some of these challenges.

Summary. A few of the scientific challenges of polar research are reviewed, with stress on the work being done by U.S. investigators. The accomplishments that have been made are impressive, but much remains to be done. An evaluation of future research goals and priorities in science per se and in the national interest is not attempted, but a research strategy for the future, presently planned by the National Research Council's Polar Research Board, should contribute to this end.

The discussion stresses research being done by U.S. investigators. For the Arctic, this research is broadly divided among a number of agencies and private groups. For the Antarctic, the responsibility is centered in the National Science Foundation (NSF) Antarctic Research Program, under whose auspices the many advances to date have been made.

It is sometimes useful to distinguish between disciplinary and problem-oriented challenges. Both types of studies are essential to polar research. Societal concerns are coming increasingly to the fore, and the fact that the polar environment is still a societal frontier gives rise to some especially important problem-oriented challenges. Only a few broad outlines from today's perspective can be compiled here, but I hope that a series of both disciplinary and problem-oriented studies will be undertaken by the National Research Council's Polar Research Board (PRB) during the next few years and that these programs will be sufficiently searching to help guide polar research to the year 2000 (*3*).

The term "polar" is here broadly interpreted to apply primarily, but not exclusively, to high-latitude regions within the Arctic and Antarctic circles (Figs. 1 and 2). There are obvious and highly significant differences between the two polar regions (*1*, *4*). The Arctic comprises an ocean of some 14×10^6 square kilometers surrounded by land, has no large grounded ice masses except the Greenland Ice Sheet (some 1.8×10^6 km^2 in extent), is characterized by an appreciable land fauna and flora, and is inhabited in many places by indigenous peoples as well as by immigrants from the south. By contrast, the Antarctic comprises a continent surrounded by the Southern Ocean totaling some 36×10^6 km^2 (about 10 percent of the world's oceans), is characterized by the Antarctic Ice Sheet (actually two joined ice sheets abutting along the Transantarctic Mountains, the East Antarctic Ice Sheet with a maximum known thickness of some 4000 meters and the smaller, partly marine-based West Antarctic Ice Sheet) covering an area of 13.5×10^6 km^2 and representing 90 percent of the world's ice (*2*), has almost no land fauna or flora, and has no indigenous human population, its only inhabitants being visiting scientists and support personnel. Yet, the Arctic and Antarctic also display strong similarities, including low mean annual temperatures; oceans with seasonally varying amounts of sea-ice cover; ice sheets and glaciers, including ice shelves; alternating 6-month periods of continuous daylight and darkness at the poles; and geomagnetic disturbances and auroral phenomena.

The Atmosphere

"The apparent stability of our current climate is due in part to the efficient response of the polar heat sink to variations in energy input. If we are to understand climate, we must therefore understand the heat balance at high latitudes and the processes which can modify it" (*5*, p. 3). Yet our knowledge of the processes is quite incomplete. During the first International Polar Year in 1882–1883, the second in 1932–1933, and IGY in 1957–1958, strong meteorological programs were carried out in both the Northern and the Southern Hemispheres. From this research and the data obtained from the number of weather stations now operating in both the Arctic and the Antarctic, it might be thought that polar weather and the role of the polar regions in the world's weather machine would be well understood. This is not the case; the polar atmosphere-ice-ocean system is far too complex (*6*). Quite aside from the difficulty of forecasting polar weather because of the still considerable distances between stations, especially in the Antarctic, it has been suggested (*7*) that the weather machine is much more sensitive to happenings in the polar regions than was formerly be-

The author is chairman of the Polar Research Board, National Research Council, Washington, D.C., and professor emeritus in the Department of Geological Sciences and Quaternary Research Center, University of Washington, Seattle 98195.

0036-8075/80/0808-0643$02.00/0

lieved. An important factor is a positive feedback mechanism in which albedo, snow cover, and temperature participate.

A startling possibility is that the world's weather over periods as short as 10 to 10^2 years may in some way be modulated by the Antarctic (*8*). That the Antarctic may have a critical bearing on longer term worldwide climatic changes over 10^3 to 10^5 years, as a result of hypothetical surging (implying internal forcing factors) of the Antarctic Ice Sheet (*9*–*11*) or ice sheet disintegration by external factors (*12*–*14a*), is being given increasingly serious attention (*15*, *16*). As advanced by Wilson (*9*), large-scale ice sheet surges could increase the albedo of the Southern Ocean sufficiently to reduce world temperatures and start Northern Hemisphere glaciation; smaller events would perhaps influence shorter term temperature fluctuations (*11*). Wilson's hypothesis has been questioned on several counts, including the apparent stability of the Antarctic ice sheets during at least the past 50×10^3 years (*17*). The fact that climatic changes in the Southern Hemisphere since 14×10^3 years ago (*10*) or even 0.5×10^6 years ago (*18*) appear to have preceded those in the Northern Hemisphere is consistent with the importance of the Antarctic in such changes; however, a lead time in climatic change does not necessarily support the view that the Antarctic was

Fig. 1. Arctic research stations.

the forcing factor, since the lag could reflect a difference in reaction time to a common event (*16, 19*).

Clearly, polar climatic changes are important in reconstructing worldwide climatic changes and their variation with latitude, information that bears strongly on the still unknown causes of such changes. At least recent temperature changes appear to have been larger in both polar regions than elsewhere (*20*). Evidence on paleoclimates can come from numerous sources—sedimentology, paleontology, palynology, paleosols, glacial geology, periglacial (frost-action) features, and ice cores (discussed below in connection with the cryosphere). All these avenues of investigation are being actively pursued.

Another important focus for research is the variation in the carbon dioxide (CO_2) content of the atmosphere (*21*). There is reason to believe that the increasing emission of CO_2 will cause warming (*16, 22–24*). Furthermore, according to some investigators, the amount of CO_2 could double by early in the next century, leading to an average 2° to 3°C warming of the world's climate, an increase that might be three to four times greater at the poles than in the tropics (*25*). A recent National Academy of Sciences report estimates ". . . the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ± 1.5°C" (*22*, p. 2). Other estimates range from an average global warming of 1° to 4°C to an increase of between 2°C and > 7°C (*26*) at high latitudes. Considering all anthropogenic effects, an estimate of a > 10°C increase in polar regions by the year 2050 has been cited as reliable "within a factor of about two" (*26*, p. 74). Changes approaching these magnitudes would have drastic climatic implications for the extent of Arctic sea ice and the movement of ships. With a significant decrease in sea ice, further changes in climate would likely ensue over a much wider region with attendant economic implications. In the Antarctic, warming could cause breakup of blocking ice shelves and might lead to ice sheet advances, perhaps sufficient to raise sea level by 6 m within two centuries (*25*), although this estimate is speculative. The recent trend in polar areas is toward cooling instead of warming (*27*), and the relationship between CO_2 and climate is replete with unanswered questions, including an apparent significant discrepancy between current theory and experiment (*28*). In any event, the polar regions clearly constitute a special focus for monitoring changes in atmospheric CO_2 and climate.

The dynamics of polar climate and the role of the polar regions in climatic change are the focus of a PRB review chaired by Dr. J. Murray Mitchell, Jr., as a contribution to the current U.S. Climate Program.

The upper atmosphere may influence the lower atmosphere in a number of ways, for example, the coupling of upper atmosphere winds to lower atmosphere energy. "The high atmosphere boundary could effect the propagation and attenuation of the larger planetary waves believed to be important in determining circulation behavior" (*29*, p. 416). The Antarctic continent is especially well located for such studies, in part because of its near-spherical ice surface offset from the geographic axis (*29*).

A unified view of the electrodynamic system of the atmosphere-ionosphere-magnetosphere requires a coordinated scientific effort to study the energy transfer processes in the high-latitude magnetic field line regions of the magnetosphere-ionosphere system. The importance of such an effort is highlighted by a priority recommendation of the National Research Council's Geophysics Research Board (*30*).

Electrical coupling between the upper and lower atmospheres is an important element in atmospheric dynamics (*31*). Two important sources of the geoelectric field (typically 100 to 200 volts per meter at the earth's surface) are global thunderstorm activity and interactions of the solar wind with the magnetosphere. The Antarctic continent provides a number of sites, including Vostok and the South Pole (Fig. 2), that are well suited for studies of both the tropospheric and the magnetospheric sources and any coupling between them.

The Arctic and Antarctic are critical regions for the study of radio communications and solar-terrestrial physics. Radio signals can be drastically affected by charged particles that are emitted during solar flares and are responsible for magnetic storms. These particles, which also cause auroras, are best studied at high latitudes. Moreover, "If magnetospheric processes such as auroras can be understood, they may provide clues to other plasma phenomena; for example, those that have until now prevented the practical harnessing of fusion plasma processes" (*2*, p. 153).

Some very low frequency electromagnetic signals, lightning caused or artificially generated, are injected into the ionosphere and the overlying magnetosphere and flash between hemispheres along the earth's magnetic field lines, interacting with other particles and leading to ionization, x-rays, and optical effects. Such enhancement of ionization and x-rays affects radio propagation and can cause the signals from VLF stations communicating with submarines and ships to vary in intensity. Some of the processes are best studied at matching high-latitude conjugate points in each hemisphere where paths converge toward the ground (*32, 33*). Harmonic radiation from electrical power transmission lines, for instance in Quebec, can leak into the magnetosphere to behave in this manner as discovered by readings in the Antarctic (*34*). Such upper atmosphere disturbances can produce ". . . modulation of ionospheric currents which in turn can induce excessive voltages in power lines, causing power blackouts" (*33*, p. 132).

The Hydrosphere

We do not have adequate knowledge of the physical, chemical, or biological oceanography of either the Arctic Ocean or the Southern Ocean. We also know little about the bottom sediments of these oceans, discussed below in the section on the lithosphere.

In physical oceanography "at the longer time scales of tens of years to centuries, account must be taken of the abyssal circulation of the ocean and the processes leading to the sinking of water to greater depths in the polar regions. The problems involved will have to remain in the realm of research for the present due to the difficulty of observation" (*24*, p. 47). With respect to the Arctic, "a real understanding of currents in the Arctic Ocean and their driving forces will exist when it is possible to predict how the circulation would be altered by changes in winds, ice cover, precipitation, and entrance size. An ability to predict seems to lie far ahead" (*2*, p. 59). Moreover, "to significantly improve the understanding of the Arctic Ocean heat budget and the controlling processes . . . [it will be necessary to] carry out synoptic mappings of meso- and large-scale (i.e., 10^1–10^3 km) salinity and temperature fields in the upper 1,000 m. Available coverage is not synoptic and is grossly inadequate both in the horizontal and vertical" (*5*, p. 88).

The problems are legion, although the situation has improved since 1970 (*35*), and important data resulted from the recently concluded Arctic Ice Dynamics Joint Experiment, in which sea-ice camps were used to examine air-sea-ice interactions in the Beaufort Sea (*36*). One of the pressing needs ". . . is for

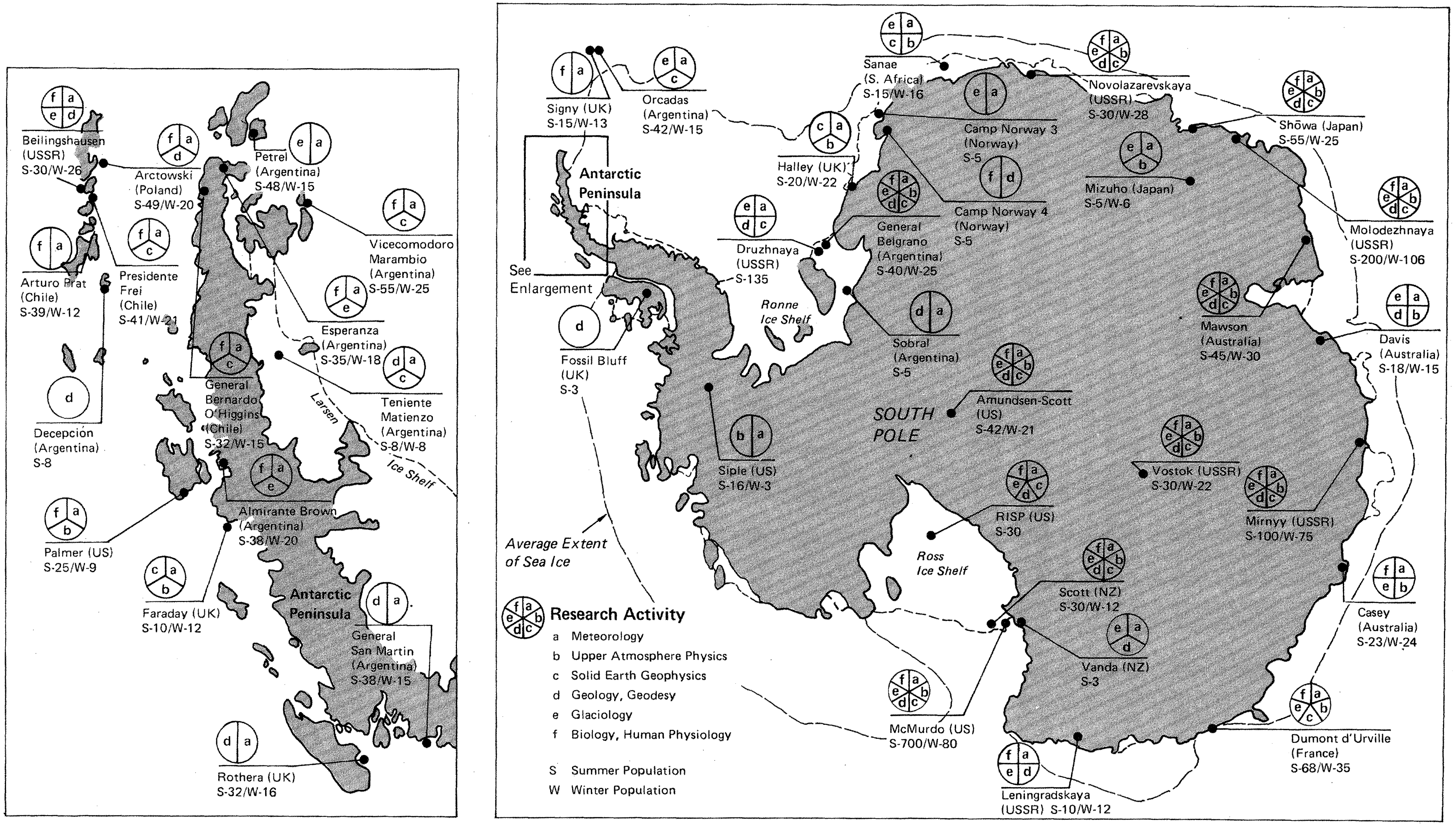

Fig. 2. Antarctic research stations.

better information on the ice and seawater exchange between the Arctic and Atlantic Oceans, which takes place between Greenland and Svalbard [Fram Strait]'' (*2*, p. 59), as stressed in 1970 (*2*) and recently reemphasized (*5*). Such work is becoming a focus for cooperative efforts between Canadian, Scandinavian, and U.S. scientists (*37*). Temperatures of the subpolar North Atlantic Ocean during the last few million years bear significantly on theories of Northern Hemisphere glaciation; whether the ocean was warm or cold affords a possible test of opposing views. Thus a rapid buildup of ice is expected as the result of warm water adjacent to snow- and ice-covered coasts—a past condition consistent with isotopic evidence and rather similar to contemporary conditions (*38*).

The Arctic Ocean is of considerable strategic interest (*39*), and, because nuclear submarines are capable of operating beneath the protective ice cover of the Arctic Ocean, oceanographic data to facilitate or detect such operations are of great interest. The acoustical characteristics of different Arctic water masses are one type of such data.

The Antarctic Circumpolar Current (or West Wind Drift) is the world's largest ocean current, yet it is still imperfectly understood (*40, 41*). The Antarctic Convergence (or Polar Front Zone), where cold Antarctic water dips beneath warmer, more saline water from the north, is one of the Southern Ocean's most important features. Lying mainly between 50°S and 60°S (*42*), it forms the northern boundary of the Southern Ocean and promises to become a critical boundary for international conventions related to the Southern Ocean, yet the seasonal variations in the position and structure of the Antarctic Convergence are not well known. Although bottom water originating in the Antarctic accounts for far more than half of the bottom waters of the world's oceans, its exact mode and place of origin remain a problem (*2, 40*).

The situation in biological oceanography is similar. The living resources of the polar oceans are coming under increasing scrutiny with respect to the world's food supply. Various international agreements have been drawn up to control fishing and whaling. A convention on sealing has been undertaken by the Antarctic Treaty Nations, but otherwise a regime to control the living resources of the Southern Ocean is still pending (*42a*). Such agreements and the United Nations Conference on the Law of the Sea require detailed scientific information, much of which is still lacking for the polar oceans. Lack of scientific information on the number of bowhead whales in the Arctic and on their reproduction has led to bitter confrontations between the International Whaling Commission and Alaskan Eskimos, and even between different agencies of the U.S. government (*43*). The adaptation of fishes to cold is of considerable interest, and new information on how some fishes adjust to water at temperatures below 0°C is now becoming available (*44*). The relations between ecosystem stability, diversity, and productivity in the polar oceans are complicated and different from those nearer the equator. A study of these factors should contribute significantly to our knowledge of the polar oceans and also to ecological theory (*45*). Insights into Antarctic life below ice shelves 400 to 600 m thick and 430 to 475 km from the open Ross Sea were recently obtained from an examination of crevasses and as a result of drilling through the Ross Ice Shelf (*46*).

With recognition of the need for sound management of the Southern Ocean ecosystem, enactment of a Convention for the Conservation of Antarctic Marine Living Resources has become a focal issue for the Antarctic Treaty Nations (*47*). The realization that the potential yield of protein-rich Antarctic krill (*Euphausia superba*) may be two to three times that of the present annual production of fishes from the world's oceans has led a number of nations to investigate the exploitation of this resource (*48*), although the economic problems accompanying commercial harvesting are considerable (*49*). Krill is a critical element in the Antarctic food chain for fishes, whales, seals, penguins, and some other birds, yet details of its life cycle and actual abundance and the effect of its exploitation on the rest of the food chain remain to be determined (*50*), including competitive effects between marine mammals and fisheries (*51*). Study of almost the entire marine ecosystem is therefore of high priority, and the International Council of Scientific Unions' Scientific Committee for Antarctic Research (SCAR) and Scientific Committee on Ocean Research (SCOR) proposed an international program (BIOMASS) to aid in this effort (*52*). A National Research Council committee, chaired by Dr. John H. Steele and representing the Ocean Sciences Board and the PRB, has just been appointed to review and recommend the nature of the U.S. research participation.

The difficulty of navigating in ice is an obvious deterrent to research in the polar oceans. In the Arctic, sea-ice platforms supplemented by aircraft operations have been used for special coverage; although this procedure has certain advantages for some programs, it is impractical for others. In the Antarctic, most of the U.S. work has been restricted to largely ice-free sectors as in the Drake Passage research (*53*) of the International Southern Ocean Studies program (*54*). Only the ice-strengthened *ARA Islas Orcadas* (formerly the USS *Eltanin*), which has been operated jointly by the NSF and the Instituto Antarctico Argentino, and the small wooden ship, *Hero*, operated by the NSF, have been available for research where ice is common. Now returned to the U.S. Navy, the *Eltanin/Islas Orcadas* has been decommissioned and would require major overhaul before she could resume Antarctic service; moreover, the *Hero*, now aging, is too small for much of the necessary work. The powerful U.S. Coast Guard ice breakers are not designed as research vessels, nor is research support normally part of their mission. As a result, the present U.S. oceanographic research capability in polar waters is at a nadir as compared with a number of other nations, just at a time when some oceanographic problems in pack-ice areas are becoming increasingly urgent.

A host of scientific problems, associated with other parts of the polar hydrosphere (lakes and streams), are not addressed here, except for one particular finding. In the Wright Dry Valley of Antarctica where the mean annual air temperature is about −20°C, the water temperatures near the bottoms of some lakes with a perennial ice cover are as high as 25°C (Lake Vanda). This condition is due not to volcanic heat but to the generally snow-free ice cover transmitting and trapping solar radiation that heats dense saline water, which remains on the bottom storing the energy (*55*).

The Cryosphere

The ice sheets characterizing Greenland and the Antarctic are similar to those that covered large parts of North America, Europe, and Eurasia at various times during the Pleistocene (10^4 to 1.8×10^6 years ago). The East Antarctic Ice Sheet developed much earlier, probably in the Middle Miocene (10.5×10^6 to 15×10^6 years ago), and the West Antarctic Ice Sheet presumably somewhat later, although there is evidence of some glaciation in the Ross Sea region of West Antarctica as early as the Late Oligocene (22.5×10^6 to 30×10^6 years ago). By the Early Pliocene (3×10^6 to 5×10^6 years ago), the continent was largely ice-covered and has probably remained so since then with some variations in the extent of the ice (*16, 19, 56, 57*).

The idea that the Antarctic ice sheets might be subject to surging or disintegration was noted above in the section on the atmosphere. In the case of the West Antarctic Ice Sheet, which is believed to be less stable than the East Antarctic Ice Sheet, it has been estimated that large-scale events could raise world sea level by 3 to 6 m (*14a, 16*) and that smaller events during the past 6×10^3 years may have raised sea level repeatedly by some 2 m within periods of a few hundred years (*11*). However, such Antarctic events have not been demonstrated. There is increasing evidence that the combination of changing earth-sun relationships as formulated by M. Milankovitch coincides with, and may be a fundamental cause of, glacial climates (*58, 59*). Yet the mechanism and quantitative adequacy of the effect pose major difficulties, and the nature of the climatic changes responsible for the present ice sheets and for the growth and decay of the Pleistocene glaciers are still problematical. The moisture sources and mechanisms permitting the growth of the Northern Hemisphere ice sheets also remain to be established (*38*).

The present ice sheets are a storehouse of information. Drilling has led to the recovery of cores that contain a stratigraphic record of climatic change as determined from variations in the isotopic ratios of ^{18}O to ^{16}O, which in turn relate to temperature and sea-level changes as controlled by the growth of ice sheets and the return of their water to the oceans upon deglaciation. The story is far from simple (*60*). Furthermore, ice cores contain a record of variations in atmospheric dust from volcanic eruptions that may be a factor in climatic change (*16, 61*). It has been suggested that chemical dating of ice cores and the analysis of the nitrate concentration may provide information on solar activity during the past 50×10^3 years (*62*). If there were significant changes, they might induce glacial climates. Ice cores are also valuable in an evaluation of global pollution effects, including the possibility that Arctic haze is due to industrial smog (*63*).

Because drilling is very expensive, a key question is how extensive a coring program should be. One must determine exactly where a core should be drilled and to what depth to maximize the information and minimize the cost. There are various complicating factors. Because of ice flow, the present location of the ice is not the same as the location where the ice originated as snowfall. Furthermore, the dynamics of ice sheets are incompletely known. In the case of the West Antarctic Ice Sheet, about 90 percent of the ice is drained by 21 glaciers (*13*), and recent observations of Byrd Glacier show that velocities can be as high as 800 m per year (at the grounding line), which is within the lower velocity range of surging alpine glaciers and suggests a potential surging mode (*64*). These and allied problems are to be examined by the PRB Glaciology Committee under the chairmanship of Dr. Charles R. Bentley.

The former extent of Pleistocene ice sheets is least well known in polar regions. A question that has recently emerged is the extent of former marine-based Arctic ice domes and of ice shelves formed of glaciers that extended into the fringing ocean as floating or grounded ice. Perhaps an Arctic Ice Sheet covered a large part of the Arctic Basin, representing considerably greater glaciation than formerly thought (*65*); there is also evidence to the contrary (*66*). Greater glaciation of the Arctic Basin would change estimates of the volume of Pleistocene ice, although in the case of a floating ice sheet not the amount of postglacial sea-level rise.

Sea ice covers most of the Arctic Ocean all year and, along with icebergs, comprises a wide belt of seasonally changing perimeter surrounding the Antarctic continent. The floating ice in both regions is a highly significant climate factor. "The ice problem is complex, involving ocean currents, and will only be solved by successful modelling based upon observation" (*24*, p. 47). The floating sea ice of both regions is also a major hindrance to navigation. In the Arctic, it is of current concern in connection with the exploration and exploitation of hydrocarbons, not only because of the difficulty of navigation but also because of its potential effect on fixed installations on the ocean bed. The power of moving pack ice is awesome. Unfortunately, the mechanics of floating ice are not well understood, another problem that demands attention.

The possibility that Antarctic icebergs could be towed to arid regions to provide a source of freshwater has received considerable attention (*67*) but, as has been noted (*68*), rather little hard-headed research. Some icebergs derived from shelf ice have been reported to have a surface area up to about 7000 km^2 (*69*), much too large for towing, but calculations suggest that towing icebergs on the order of up to 2 km long and 0.5 to 2 km wide to arid parts of Australia warrants further research and possible testing (*70*).

Permafrost (ground at a mean annual temperature below 0°C for a period of 2 years or more) commonly contains ice and is therefore also part of the cryosphere. In polar regions permafrost extends to depths exceeding 500 m in places (*71*) and can pose serious difficulties for engineering projects, as in the construction of the trans-Alaska pipeline. Here the problem was the high temperature of the oil and the need to avoid unacceptable pipe stresses that could be caused by the melting of ground ice as the result of pipe burial. The inverse problem is presented by the proposed cold-gas pipeline, which could induce freezing and frost heaving of the ground that might cause unacceptable stresses. The discussion reflects our still inadequate knowledge of three-dimensional coupled heat and mass transfer in freezing soils.

The recent discovery of offshore (subsea) permafrost presents difficulties for oil and gas exploration along the Arctic coast of Alaska, and similar difficulties will probably occur off other polar coasts where hydrocarbons are sought. To determine the full extent and depth of such permafrost occurrences is another focus of contemporary research (*72*).

The Lithosphere

Innumerable unresolved problems pertain to the lithosphere in both polar regions. The unconsolidated sediments of the Arctic Ocean and Southern Ocean provide evidence of prime importance on climatic changes. Acquisition of deep cores is a priority research need to resolve problems relating to the timing and extent of pack-ice cover during late Cenozoic time. This in turn has implications for the nature and causes of climatic change.

Surface samples and shallow cores (up to 3.8 m long) have been recovered from the Arctic Ocean. Of these, only two cores contained sediments older than Pliocene (*73*). The sedimentological and paleontological information obtained has been variously interpreted as indicating that the Arctic Basin was free of permanent pack ice in the interval from 0.7×10^6 to 2.4×10^6 years ago and that after this time four to six fluctuations of permanent versus seasonal pack ice occurred (*74*), or that pack ice has been continuously present for the past 3×10^6 or 3.5×10^6 years (*57, 73*).

Those parts of the Southern Ocean that are relatively free of pack ice have been the sites of significant drilling as part of the NSF Deep Sea Drilling Project. This drilling penetrated deeply enough to obtain a highly interesting Cenozoic record that sheds light on the climatic history of that period (*57*), but places where the pack ice is heavier, as over the continental shelf, ". . . are less well surveyed than any portions of the World's ocean with the exception of the Arctic Ocean. . . . If an informed estimate of the potential of offshore Antarctic resources is a goal of the U.S., then an extensive program of exploration surveying is required for 95% of the continental shelf and adjoining areas" (*75*, p. B8).

There are many questions regarding the earlier history and structure of the lithosphere in both polar regions. In the Arctic, the structure of the ocean basin is not known in detail. Work is going forward, especially from sea-ice platforms as in the Lomonosov Ridge Experiment (*76*), but much remains to be done.

"Scientific problems that relate to the continental margins bordering the Arctic Ocean must be assessed differently from those of other continental margins. So little is known of the area, and the working conditions are difficult. We know at least one order of magnitude less about Arctic marine geology and geophysics than about any other areas. Not even the broad tectonic framework of the area has been adequately described. We urgently need to collect basic geological and geophysical data on the margins and in the deep basins. Collecting data in the Arctic is complicated by the extreme difficulty of working in a hostile environment, much of which is ice-covered. More than anywhere else, there is need for cooperative programs in the Arctic, not just between individuals and organizations but also between nations" (*77*, p. 102). Stratigraphic and structural data are being eagerly sought because of their bearing on exploration for hydrocarbons.

Geologic research in the Antarctic since the IGY has virtually confirmed the hypothesis that the continent was once part of Gondwanaland, a supercontinent that broke up during the Mesozoic era (from 2.25×10^6 to 65×10^6 years ago) and whose other fragments are now represented by Africa, Australia, India, and South America (*78*). However, some important aspects of the supercontinent reconstruction remain controversial (*79*).

Because the continent is 98 percent ice covered, many aspects of Antarctic geology are very poorly known (*80*). The structural relations between East and West Antarctica pose a large-scale problem, and there are many smaller ones. Information on possible mineral resources is very scarce. There is reason to believe that the sediments of the continental shelf may contain large hydrocarbon resources and that some of the continental areas, such as the Dufek Massif, may contain valuable mineral deposits, but there has been too little exploration to permit more than reasonable speculation (*81*).

The Biosphere

Some deficiencies in our knowledge of the biosphere were cited in the section on the hydrosphere. There are many others. Among the biological challenges pertinent to both polar regions is how the various terrestrial life-forms have adapted to their environment (*4, 82*). Among the problems relevant to the Arctic are the circumpolar distribution of certain plant species and the endemic nature of others (*83*). The existence and migration routes of early Tertiary temperate- to warm-temperature floras and faunas, including alligators, at high Arctic latitudes raise interesting questions, since the latitudes were apparently similar to today's and entailed a polar light-dark regime (*84*). The reasons for the disappearance of a number of Pleistocene mammals, such as *Bison priscus* (giant bison), *Cervalces* (giant deer), *Mammuthus primigenius* (woolly mammoth), *Mastodon americanus* (mastodon), and *Symbos* (woodland musk-ox), in Alaska and elsewhere are not known (*85*). Possibly, as in northeastern Asia (*86*), they were unable to survive the postglacial warmth and attendant vegetational changes, which in much of Alaska represented mainly a change from grassland (or Arctic steppe) to coniferous forest (*87*). Ancient hunters could be another factor (*88*).

Of more immediate concern is the nature of scientific information necessary for the institution of sound management practices for northern forests and wildlife, and sound estimates of agricultural potential in the north to meet possible future needs. For instance, the development of mold-resistant strains of winter wheat may well increase the northward range of this grain in the near future (*89*). Another concern is the effect of oil spills on Arctic vegetation (*90*). In ecosystem studies, the Tundra Biome Program of the International Biological Program has done much to stimulate biological work in the Arctic and to define critical research needs (*91*). Among these is the need for better data on the amount of carbon and the carbon flux in the tundra and boreal forest; the quantities involved may bear critically on the estimates of CO_2-induced climatic change (*92*).

The study of Antarctic birds, especially penguins, is reasonably advanced. Penguins spend most of their life at sea but nest on land; the emperor penguin (*Aptenodytes forsteri*) withstands temperatures during the Antarctic night as low as −60°C. Seals are primarily sea mammals, but they pup on land and have been known to wander far inland. Aside from the above, native land life is essentially limited to one wingless insect (*Belgica antarctica*, a midge confined to the Antarctic Peninsula), various species of Collembola and mites [some having a freezing tolerance of −60°C or lower (*93*)], two species of flowering plants (confined to the Antarctic Peninsula), and some lichens, mosses, and aquatic algae including the prominent *Nostoc*; a remarkable collection of blue-green algae and other microorganisms inhabit the near-surface zone of some rocks (*94*). As a natural laboratory for the study of primitive life at the limits of tolerance, the Antarctic has few equals. As such, studies conducted in the Antarctic are relevant to space research as well as to our planet.

Peoples

One of the currently active and highly controversial research areas is the peopling of the Americas. It is generally conceded that immigration was from Asia to Alaska, but when and even how are debatable. It appears that immigration into Alaska would have been possible from about 10^4 to 2.8×10^4 years ago during the last glaciation, when lowered sea level for most of the period exposed the Bering Land Bridge. Beginning some 10^4 to 1.4×10^4 years ago as glaciers receded, peoples presumably moved south along an ice-free corridor between the Cordilleran Ice Complex and the Laurentide Ice Sheet (*95*). However, there is considerable uncertainty about the timing (*96*) and even about the necessity of a late Wisconsin corridor (*97*). Moreover, it has not been demonstrated that immigration could not have occurred across the Bering Strait on winter ice or possibly in skin boats during interglaciations when glacial barriers would have been absent. There is suggestive evidence that people were in North America by 2×10^4 years ago or even earlier (*96, 98*), and the entire problem is clearly a major research challenge.

Another challenge is the rapidly changing life-styles of native peoples in the Arctic, especially the North American Eskimo. Ancient customs have been endangered or abandoned, as defense installations, mining, and oil exploration and exploitation became part of the Arctic scene. Snowmobiles have replaced the dogsled, and larger settlements are replacing small native villages. Drug abuse has become a problem in places. Settlement of the Alaskan native land claims has brought financial resources to native cooperatives, and the natives have developed a voice (*99*) and political clout that are significantly influencing how things are handled in the Arctic. All these developments entail societal questions requiring careful study.

In the Antarctic new socioeconomic issues are surfacing. Women scientists and staff are now a part of what had been a man's world, and adjustments are being made. Tourism is now a factor with its attendant problems of interference with busy scientists and unwished responsibility for the safety and welfare of the visitors.

International Aspects

Both the Arctic and Antarctic are politically sensitive areas. In the Arctic, defense considerations are overriding because of strategic implications. The principal Soviet naval base is on the Kola Peninsula from which nuclear submarines with long-range nuclear missiles have wide maneuverability beneath the Arctic sea ice and close access to the North Atlantic (*39*). Delicate issues arise over continental shelf rights around Svalbard (Fig. 1), over which Norway has sovereignty but which has been internationalized by the Svalbard Treaty (*100*). Such political considerations are a deterrent to cooperation between East and West in Arctic research, especially oceanographic research. In the Arctic, unlike the Antarctic, the diversity of problems and interests has thus far prevented a succinct, comprehensive, and public statement of U.S. policy that might help to guide Arctic research and affect decisions such as the closing of the Navy's Arctic Research Laboratory (*101*).

Long-standing national claims are temporarily muted in the Antarctic Treaty under a formula by which claims are held in abeyance without prejudice during the life of the treaty. This treaty, which grew out of the spirit of scientific cooperation during the IGY, runs until at least 1991, when a review conference can be called for by any of the signatory nations (*102*), and will continue thereafter unless abrogated. Because the treaty is silent on resource exploitation, SCAR (*103*) has been active in furthering conservation measures, and the signatory nations have debated the issues at recent treaty conferences. The political issues are complex (*102, 104, 105*). The prospect of possible future economic benefits from krill harvesting and mineral exploitation is already putting strains on the treaty's future, not only from the signatory nations (*106*) but also from other countries that are tempted to regard these nations as an exclusive club with selfish motives (*105, 107*). To help resolve issues before they might become acute, the signatory nations are working on a conservation regime for the Southern Ocean (*42a, 47, 102, 105*). It is anticipated that a subsequent step will be consideration of a regime to control any future exploration and exploitation of mineral resources including hydrocarbons (*42a, 105*). Whether significant deposits exist is still unknown but the possibility appears reasonable, and in preparation for a regime to control the exploitation of mineral resources a series of studies has been carried out on possible environmental effects of exploration and exploitation (*108*). These studies demonstrate the need for rather specific information, presently lacking, on the biology, climatology, geology, geophysics, and physical oceanography of Antarctica before a number of the questions can be satisfactorily answered. The nature of the resources and the economics of possible mineral exploitation with appropriate environmental safeguards will presumably determine the extent to which any exploitation will occur (*109*). Some influential environmental groups would make Antarctica a World Preserve closed to all mineral exploitation until protection of the marine and terrestrial ecosystems is assured (*110*).

Policy goals for U.S. research in Antarctica have been summarized as follows (*111*, p. 96):

"1) To maintain the Antarctic Treaty and insure that this continent will continue to be used for peaceful purposes only and shall not become an area or object of international discord.

"2) To foster cooperative scientific research for the solution of worldwide and regional problems including environmental monitoring and prediction and assessment of resource potential.

"3) To protect the Antarctic environment and to develop appropriate measures to insure equitable and wise use of living and non-living resources.

"4) To promote the free exchange of information.

"5) To maintain a suitable presence in Antarctica which continues to provide leadership in development of the area and which preserves U.S. rights and protects future national interests in Antarctica."

From a scientific viewpoint (*111*, pp. 77–78),

". . . the national interest in Antarctica has important . . . significance beyond that expressed in the statement of national policy. This stems from our understanding that Antarctica:

"—exerts a major influence on how the world's oceans and atmosphere behave . . . ;

"—may contain significant living and mineral resources, the scientific understanding of which is an important base line for developing wise international management;

"—provides an outstanding opportunity and environment for international cooperation and research support . . . ;

"—because of its remoteness from the heavily populated areas of the world, provides a unique site for long-term base line measurements related to environmental pollution problems."

Thus far, the potential economic considerations that arise from the self-interests of nations have not significantly hampered but may actually be furthering international scientific cooperation in Antarctica. If economically significant mineral resources are actually found, the treaty will be put to a severe test. The hope is that, by meeting potential problems now, the framework for handling future, more severe problems will be strengthened so that the treaty will continue and this unique example of international cooperation, which includes both the East and West, can be perpetuated. In the meantime, national interest on the part of the treaty nations would seem to dictate their continuing involvement in the effort to fulfill this hope.

Thus, in both the Arctic and Antarctic, scientific research has political and economic implications, and the resulting financial support has given impetus to research, especially in the Antarctic. Success in this opportunity to advance both science and national self-interest through international cooperation in Antarctica is a challenge, both for governments and individual scientists, that has far-reaching implications for both polar hemispheres.

Note added in proof: A preprint of an important article bearing on the polar atmosphere-ice-ocean processes was received after this article was in galleys (*112*).

References and Notes

1. G. A. Llano, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 27-61.
2. Committee on Polar Research, *Polar Research—A Survey* (National Academy of Sciences, Washington, D.C., 1970).
3. Polar Research Board, *Annual Report 1978 and Future Plans* (National Academy of Sciences, Washington, D.C., 1979).
4. B. C. Parker, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 203-229.
5. SCOR Working Group 58, *Univ. Bergen Geophys. Inst. (Div. A., Phys. Oceanog.) Rep. 52* (1979).
6. Joint U.S. POLEX Panel, *U.S. Contribution to the Polar Experiment (POLEX): part I, POLEX-GARP (Global Atmosphere Research Program) (North)* (National Academy of Sciences, Washington, D.C., 1974); Joint U.S. POLEX Panel, *U.S. Contribution to the Polar Experiment (POLEX): part II, POLEX-GARP (South)* (National Academy of Sciences, Washington, D.C., 1974).
7. W. W. Kellogg, in *Climate of the Arctic*, G. Weller and S. A. Bowling, Eds. (Univ. of Alaska Press, Fairbanks, 1973), pp. 111-116.
8. J. O. Fletcher and J. J. Kelley, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 97-116; J. O. Fletcher, *Mon. Weather Rev.*, in press.
9. A. T. Wilson, *Nature (London)* **201**, 147 (1964).
10. ______, in *Antarctic Glacial History and World Paleoenvironments*, E. M. Van Zinderen Bakker, Ed. (Balkema, Rotterdam, 1978), pp. 15-23.
11. ______, in *ibid.*, pp. 33-39.
12. T. Hughes, *J. Geophys. Res.* **78**, 7884 (1973).
13. ______, *Rev. Geophys. Space Phys.* **15**, 1 (1977).
14. R. H. Thomas and C. R. Bentley, *Quat. Res. (N.Y.)* **10**, 150 (1978).

14a. R. H. Thomas, T. J. O. Sanderson, K. E. Rose, *Nature (London)* **277**, 355 (1979).

15. W. F. Budd and B. J. McInnes, *Hydrol. Sci. Bull.* **24**, 95 (1979).
16. H. Flohn, in *Antarctic Glacial History and World Paleoenvironments*, E. M. Van Zinderen Bakker, Ed. (Balkema, Rotterdam, 1978), pp. 3-13.
17. G. de Q. Robin, personal communication; R. M. Koerner, *Geosci. Can.* **6**, 97 (1979).
18. J. D. Hays, in *Antarctic Glacial History and World Paleoenvironments*, E. M. Van Zinderen Bakker, Ed. (Balkema, Rotterdam, 1978), pp. 57-71.
19. J. H. Mercer, in *ibid.*, pp. 73-93.
20. Climate Research Board, *International Perspectives on the Study of Climate and Society* (National Academy of Sciences, Washington, D.C., 1978).
21. Carbon Dioxide Effects Research and Assessment Program, *Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change* (Office of Health and Environmental Research, Department of Energy, Washington, D.C., in preparation).
22. Ad Hoc Study Group on Carbon Dioxide and Climate, *Carbon Dioxide and Climate: A Scientific Assessment* (National Academy of Sciences, Washington, D.C., 1979).
23. J. M. Mitchell, *EDS (Environ. Data Service, Natl. Oceanic Atmos. Admin.)* **1977**, 3 (March 1977).
24. *World Climate Conference—Declaration and Supporting Documents* (World Meteorological Organization, Geneva, 1979).
25. G. J. F. MacDonald, G. Woodwell, R. Revelle, C. D. Keeling, *Congr. Rec.* **125** (No. 104), 1 (1979).
26. W. Bach, *Prog. Phys. Geog.* **3**, 55 (1979).
27. G. J. Kukla *et al.*, *Nature (London)* **270**, 573 (1977).
28. S. B. Idso, *Science* **207**, 1462 (1980).
29. SCAR Working Group on Meteorology, *Polar Rec.* **19**, 407 (1979).
30. Geophysics Research Board, *Upper Atmosphere Research in the 1980's: Ground-Based, Airborne, and Rocket Techniques* (National Academy of Sciences, Washington, D.C., 1979).
31. N. C. Maynard, Ed., *Middle Atmosphere Electrodynamics: Report of the Workshop on the Role of the Electrodynamics of the Middle Atmosphere on Solar Terrestrial Coupling* (Publication NASA CP-2090, National Aeronautics and Space Administration, Washington, D.C., 1979).
32. R. A. Helliwell, in *Scientific Research in Antarctica* (Royal Society, London, 1977), pp. 213-224; ______ also in *Philos. Trans. R. Soc. London Ser. B* **279**, 1 (1977).
33. ______, in *U.S. Antarctic Program: Hearings Before the Subcommittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives*, 1 and 3 May 1979 (Government Printing Office, Washington, D.C., 1979), pp. 128-132.
34. C. G. Park, *Antarct. J. U.S.* **13**, 206 (1978); B. K. Hartline, *Science* **205**, 1365 (1979).
35. K. Aagaard, *Rev. Geophys. Space Phys.* **17**, 1576 (1979); L. K. Coachman and K. Aagaard, in *Marine Geology and Oceanography of the Arctic Seas*, Y. Herman, Ed. (Springer-Verlag, New York, 1974), pp. 1-72.
36. R. S. Pritchard, Ed., *Sea Ice Processes and Models: Arctic Ice Dynamics Joint Experiment—International Commission on Snow and Ice Symposium Proceedings* (Univ. of Washington Press, Seattle, 1980); N. Untersteiner, *Polar Rec.* **19**, 363 (1979).
37. K. Hunkins, Y. Kristoffersen, G. L. Johnson, A. Heiberg, *Eos* **60**, 1043 (1979); I. Dyer and A. Baggeroer, *ibid.* **61**, 34 (1980). In the same general region, the Swedish *Ymer* 80 Expedition is scheduled to visit the northern Barents Sea and the waters north and west of Svalbard and north of Greenland in 1980. With an international cadre of scientists, it will emphasize the biology of the Arctic Ocean, pollutants in the Arctic atmosphere, and the extent and chronology of the Quaternary ice sheets [*Int. Mar. Sci. Newsl. 25* (1980)].
38. W. F. Ruddiman and A. McIntyre, *Science* **204**, 173 (1979); ______, V. Niebler-Hunt, J. T. Durazzi, *Quat. Res. (N.Y.)* **13**, 33 (1980); R. G. Johnson and J. T. Andrews, *ibid.* **12**, 119 (1979).
39. H. C. Bach and J. Taagholt, *Greenland and the Arctic Region—In the Light of Defence Policies: Defence Aims* [Information and Welfare Service of the Danish Defence (Forsvarets Oplysnings- og Veldfaerdstjeneste), Copenhagen, 1977], pp. 24-30.
40. Ad Hoc Working Group on Antarctic Oceanography, *Southern Ocean Dynamics—A Strategy for Scientific Exploration, 1973-1983* (National Academy of Sciences, Washington, D.C., 1974).
41. Post-International Decade of Oceanographic Exploration Planning Steering Committee, *The Continuing Quest—Large-Scale Ocean Science for the Future* (National Academy of Sciences, Washington, D.C., 1979).
42. A. L. Gordon and R. D. Goldberg, in *Antarctic Map Folio Series, Folio 13*, V. C. Bushnell, Ed. (American Geographical Society, New York, 1970).

42a. Scientific Committee on Antarctic Research, *SCAR Bull. 64* (1980)—also in *Polar Rec.* **20**, 85 (1980); According to *Ocean Sci. News* [**22** (No. 22), 5 (1980)], "A treaty on Antarctic marine living resources will be opened for signatures. The conference on the Conservation of Antarctic Marine Living Resources ended 20 May in Canberra, Australia, with an agreement to establish a permanent commission which will have the responsibility for drawing up a series of measures for the conservation of the resources."

43. J. Bockstoce, *Natl. History* **89** (No. 5), 52 (1980); S. G. Brown, *Polar Rec.* **19**, 386 (1979); M. Reeves, *Ocean Law Memo 16* (University of Oregon, 1979).
44. A. L. DeVries, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 175-202.
45. Committee for the Nansen Drift Station, *Scientific Plan for the Proposed Nansen Drift Station* (National Academy of Sciences, Washington, D.C., 1976); R. Margalef, in *Polar Oceans*, M. J. Dunbar, Ed. (Arctic Institute of North America, Calgary, Alberta, 1977), pp. 367-376.
46. P. M. Bruchhausen, J. A. Raymond, S. S. Jacobs, A. L. DeVries, E. M. Thorndike, H. H. DeWitt, *Science* **203**, 449 (1979); J. H. Lipps, T. E. Ronan, Jr., T. E. DeLaca, *ibid.*, p. 447.
47. R. M. May, J. R. Beddington, C. W. Clark, S. J. Holt, R. M. Laws, *ibid.* **205**, 267 (1979); *The Southern Ocean Convention Workshop on Management of Antarctic Marine Living Organisms* (Center for Environmental Education–Whale Protection Fund, Washington, D.C., 1980).
48. J. D. Baker, Jr., in *U.S. Antarctic Program: Hearings Before the Subcommittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives*, 1 and 3 May 1979 (Government Printing Office, Washington, D.C., 1979), pp. 133-142.
49. R. T. Scully, *Univ. Miami Law Rev.* **33**, 341 (1978).
50. D. L. Alverson, *Ocean Dev. Int. Law J.* **8**, 171 (1980); J. L. Bengtson, *Review of Information Regarding the Conservation of Living Resources of the Antarctic Marine Ecosystem* (final report to the U.S. Marine Mammal Commission in fulfillment of contract MM 8 AD 055, 1978); G. A. Llano, *Univ. Miami Law Rev.* **33**, 357 (1978).
51. D. B. Siniff, I. Stirling, L. L. Eberhardt, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 161-174.
52. S. Z. El-Sayed, Convenor, *Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS)*, vol. 1, *Research Proposals* (Scientific Committee on Antarctic Research-Scientific Committee on Oceanic Research, Scott Polar Research Institute, Cambridge, England, 1977); S. Z. El-Sayed, Convenor, Scientific Committee on Antarctic Research *SCAR Bull. 64* (1980)—also in *Polar Rec.* **20**, 100 (1980).
53. R. D. Pillsbury, T. Whitworth III, W. D. Nowlin, Jr., F. Sciremammano, Jr., *J. Phys. Oceanog.* **9**, 469 (1979).
54. A. L. Gordon, in *Polar Oceans*, M. J. Dunbar, Ed. (Arctic Institute of North America, Calgary, Alberta, 1977), pp. 219-225; International Decade of Ocean Exploration, *Program Summary of the International Southern Ocean Studies* (NSF Division of Ocean Sciences Publication 80-4, Washington, D.C., 1980).
55. A. T. Wilson and H. W. Wellman, *Nature (London)* **196**, 1171 (1962); Y. Yusa, in *Geochemical and Geophysical Studies of Dry Valleys, Victoria Land in Antarctica*, T. Torii, Ed. (Special Issue No. 4, National Institute of Polar Research, Tokyo, 1975), pp. 75-89.
56. D. J. Drewry, in *Antarctic Glacial History and World Paleoenvironments*, E. M. Van Zinderen Bakker, Ed. (Balkema, Rotterdam, 1978), pp. 25-32; L. A. Frakes, *Climates Throughout Geologic Time* (Elsevier, Amsterdam, 1979); J. P. Kennett, in *Antarctic Glacial History and World Paleoenvironments*, E. M. Van Zinderen Bakker, Ed. (Balkema, Rotterdam, 1978), pp. 41-56. The age ranges (in years) for the Late Oligocene, Middle Miocene, Early Pliocene, and beginning of the Pleistocene as given above conform in general to those of Berggren and van Couvering (*57*).
57. W. A. Berggren and J. A. van Couvering, *The Late Neogene* (Elsevier, Amsterdam, 1974)—also in *Palaeogeog. Palaeoclimatol. Palaeoecol.* **16**, 1 (1974).
58. J. D. Hays, J. Imbrie, N. J. Shackleton, *Science* **194**, 1121 (1976).
59. J. Imbrie and K. P. Imbrie, *Ice Ages—Solving the Mystery* (Enslow, Short Hills, N.J., 1979).
60. N. J. Shackleton and N. D. Opdyke, *Quat. Res. (N.Y.)* **3**, 39 (1973).
61. J. R. Bray, *Science* **197**, 251 (1977).
62. A. T. Wilson and C. H. Hendy, *N.Z. Antarct. Rec.* **1**, 58 (1978).
63. R. A. Kerr, *Science* **205**, 290 (1979).
64. T. Hughes, personal communication.
65. D. M. Hopkins, *Am. Quat. Assoc. Abstr., Fifth Biennial Meet.*, p. 214; T. Hughes, G. H. Denton, M. G. Grosswald, *Nature (London)* **266**, 596 (1977); M. G. Grosswald, *Quat. Res. (N.Y.)* **13**, 1 (1980); D. D. Kvasov, *ibid.* **9**, 288 (1978).
66. G. S. Boulton, *Boreas* **8**, 31 (1979); J. England and R. S. Bradley, *Science* **200**, 265 (1978).
67. R. H. T. Dodson, *Focus (Rochester, N.Y.)* **29**, 10 (1978); A. A. Husseiny, Ed., *Iceberg Utili-*

zation (Pergamon, New York, 1978); P. Schwerdtfeger, *Cold Regions Sci. Technol.* **1**, 59 (1979).
68. H. Bader, in *Iceberg Utilization*, A. A. Husseiny, Ed. (Pergamon, New York, 1978), pp. 34–44.
69. C. Swithinbank, *Polar Rec.* **14**, 477 (1969).
70. W. F. Weeks and M. Mellor, *U.S. Army Corps Eng. Cold Regions Res. Eng. Lab. CRREL Rep. 78-2* (1978)—also in *Iceberg Utilization*, A. A. Husseiny, Ed. (Pergamon, New York, 1978), pp. 45–98.
71. A. L. Washburn, *Geocryology—A Survey of Periglacial Processes and Environments* (Arnold, London, 1979).
72. Ad Hoc Study Group on Offshore Permafrost, *Problems and Priorities in Offshore Permafrost Research* (National Academy of Sciences, Washington, D.C., 1976).
73. D. L. Clark, in *Polar Oceans*, M. J. Dunbar, Ed. (Arctic Institute of North America, Calgary, Alberta, 1977), pp. 603–615.
74. Y. Herman, in *Marine Geology and Oceanography of the Arctic Seas*, Y. Herman, Ed. (Springer-Verlag, New York, 1974), pp. 283–348; for more recent information, see Y. Herman and D. M. Hopkins, *Science* **209**, 557 (1980).
75. D. E. Hayes, in *A Framework for Assessing Environmental Impacts of Possible Antarctic Mineral Development*, D. H. Elliott, Ed. (Institute of Polar Studies, Ohio State University, Columbus, 1976), vol. 2, appendix, part B.
76. J. R. Weber, *Eos* **60**, 715 (1979).
77. Ocean Sciences Board, *Continental Margins—Geological and Geophysical Research Needs and Problems* (National Academy of Sciences, Washington, D.C., 1979).
78. P. F. Baker and D. H. Griffiths, in *Scientific Research in Antarctica* (Royal Society, London, 1977), pp. 143–159—also in *Philos. Trans. R. Soc. London Ser. B*. **279**, 1 (1977); C. Craddock, in *Polar Research—To the Present, and the Future*, M. A. McWhinnie, Ed. (Selected Symposium 7, AAAS, Washington, D.C., 1978), pp. 62–96; in *Third International Gondwana Symposium (Calcutta, 1977) Papers*, B. Laskar and C. S. R. Rao, Eds. (Hindustan, Delhi, India, 1979), vol. 1, pp. 711–771; J. Sutton, in *Scientific Research in Antarctica* (Royal Society, London, 1977), pp. 197–205—also in *Philos. Trans. R. Soc. London Ser. B* **279**, 1 (1977).
79. C. G. A. Harrison, E. J. Barron, W. W. Hay, *Geology* **7**, 374 (1979); I. W. D. Dalziel, *ibid.* **8**, 260 (1980); E. Godoy and C. Mpodozis, *ibid.*, p. 261; C. G. A. Harrison, E. J. Barron, W. W. Hay, *ibid.*, p. 262.
80. V. C. Bushnell and C. Craddock, Eds., *Antarctic Map Folio Series, Folio 12* (American Geographical Society, New York, 1970); C. Craddock, *Geologic Map of Antarctica, 1:5,000,000* (American Geographical Society, New York, 1972).
81. J. H. Zumberge, *Am. Sci.* **67**, 68 (1979).
82. R. S. Hoffman, in *Arctic and Alpine Environments*, J. D. Ives and R. G. Barry, Eds. (Methuen, London, 1974), pp. 475–568.
83. A. Löve and D. Löve, in *ibid.*, pp. 571–603.
84. R. M. West and M. R. Dawson, *Polarforschung* **48**, 103 (1978).
85. D. K. Grayson, in *Advances in Archaeological Method and Theory*, M. B. Schiffer, Ed. (Academic Press, New York, 1980), vol. 3, pp. 357–403; P. S. Martin and H. E. Wright, Jr., Eds., *Pleistocene Extinctions—The Search for a Cause* (Yale Univ. Press, New Haven, Conn., 1967).
86. C. C. Flerow, in *The Bering Land Bridge*, D. M. Hopkins, Ed. (Stanford Univ. Press, Stanford, Calif., 1967), pp. 271–280.
87. R. D. Guthrie, *Am. Midl. Nat.* **79**, 346 (1968); J. V. Matthews, Jr., *Beringia During the Late Pleistocene: Arctic-Steppe or Discontinuous Herb-Tundra? A Review of the Paleontological Evidence* (Open File Report 649, Canada Geological Survey, Ottawa, 1979). A report by L. C. Cwynar and J. C. Ritchie [*Science* **208**, 1375 (1980)], received while this article was in press, argued for a sparse tundra in Eastern Beringia.
88. P. S. Martin, *Science* **179**, 969 (1973); in *Arctic and Alpine Environments*, J. D. Ives and R. G. Barry, Eds. (Methuen, London, 1974), pp. 669–700.
89. F. J. Wooding, in *Science in Alaska: 30th Alaska Science Conference Proceedings* (AAAS and American Chemical Society, Washington, D.C., 1979), pp. 60–61.
90. D. A. Walker, P. J. Webber, K. R. Everett, J. Brown, *Arctic* **31**, 242 (1978).
91. L. C. Bliss, O. W. Heal, J. J. Moore, Eds., *Tundra Ecosystems: A Comparative Analysis* (Cambridge Univ. Press, Cambridge, England, in press).
92. W. H. Schlesinger, in *The Role of Terrestrial Vegetation in the Global Carbon Cycle*, G. M. Woodwell, Ed. (Wiley, New York, in press).
93. J. S. Edwards, personal communication.
94. E. I. Friedmann, *Antarct. J. U.S.* **12**, 26 (1977); *ibid.* **13**, 162 (1978).
95. D. M. Hopkins, in *The Bering Land Bridge*, D. M. Hopkins, Ed. (Stanford Univ. Press, Stanford, Calif., 1967), pp. 451–484; H. J. Müller-Beck, in *ibid.*, pp. 373–408; D. M. Hopkins, in *The First Americans: Origins, Affinities, and Adaptations*, W. S. Laughlin and A. B. Harper, Eds. (Fischer, New York, 1979), pp. 15–41.
96. D. E. Dumond, *The Eskimos and Aleuts* (Thames & Hudson, London, 1977); J. B. Griffin, in *The First Americans: Origins, Affinities, and Adaptations*, W. S. Laughlin and A. B. Harper, Eds. (Fischer, New York, 1979), pp. 43–55.
97. A. M. Stalker, *Am. Quat. Assoc. Abstr., Fifth Biennial Meet.*, p. 19.
98. R. Bonnichsen, in *Early Man in America from a Circum-Pacific Perspective*, A. L. Bryan, Ed. (Occasional Paper 1, Department of Anthropology, University of Alberta, Edmonton, 1978), pp. 102–118; W. N. Irving, in *ibid.*, pp. 96–101; R. E. Morlan, in *ibid.*, pp. 78–95.
99. For instance, the Inuit Circumpolar Conference was founded in Alaska in 1977; the second meeting was held in Greenland in 1980. *The Arctic Coastal Zone Management Newsletter* (published by the North Slope Borough, Anchorage Liaison Office, Anchorage, Alaska).
100. W. Østreng, *Politics in High Latitudes—The Svalbard Archipelago* (McGill-Queen's Univ. Press, Montreal, 1978); *Concerning Svalbard* [Royal Ministry of Justice Report No. 39 to the Norwegian Storting (1974–1975), Oslo, 1975] (abridged translation).
101. G. Weller, *Arct. Coastal Zone Management Newsl. 16* (1980); L. J. Carter, *Science* **207**, 1448 (1980).
102. T. Scully, in *U.S. Antarctic Program: Hearings Before the Subcommittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives*, 1 and 3 May 1979 (Government Printing Office, Washington, D.C., 1979), pp. 2–41.
103. J. H. Zumberge, in *ibid.*, pp. 41–62; T. Gjelsvik, in *El Desarrollo de la Antárctica*, F. O. Vicuña and A. S. Araya, Eds. (Instituto de Estudios Internacionales, University of Chile, Santiago, 1977), pp. 328–344.
104. F. C. Alexander, Jr., *Univ. Miami Law Rev.* **33**, 371 (1978); M. C. W. Pinto, *ibid.*, p. 475; F. Z. Santa Cruz, *ibid.*, p. 425.
105. B. Mitchell and J. Tinker, *Antarctica and Its Resources* (Earthscan, London, 1980).
106. The original signatory nations are Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, Soviet Union, United Kingdom, and United States. Subsequently Poland joined as a consultative (full) member, and Brazil, Czechoslovakia, Denmark, Federal Republic of Germany, German Democratic Republic, Netherlands, and Romania acceded to the treaty.
107. B. Mitchell and L. Kimball, *Foreign Policy* **35**, 124 (1979); B. Roberts, in *El Desarrollo de la Antárctica*, F. O. Vicuña and A. S. Araya, Eds. (Instituto de Estudios Internacionales, University of Chile, Santiago, 1977), pp. 336–356—also in *Polar Rec.* **19**, 107 (1979).
108. M. W. Holdgate and J. Tinker, *Oil and Other Minerals in the Antarctic: The Environmental Implications of Possible Mineral Exploration or Exploitation in Antarctica* (Scientific Committee on Antarctic Research [c/o Scott Polar Research Institute], Cambridge, England, 1979); J. H. Zumberge, Ed., *Possible Environmental Effects of Mineral Exploration and Exploitation in Antarctica* (Scientific Committee on Antarctic Research [c/o Scott Polar Research Institute], Cambridge, England, 1979).
109. J. A. Dugger, *Univ. Miami Law Rev.* **33**, 315 (1978).
110. J. N. Barnes, in *Earthscan Press Briefing Seminar on Antarctic Resources and the Environment* (Earthscan, Washington, D.C., 14 September 1979), appendix 2; *Living Wilderness* **43**, 32 (1979).
111. R. C. Atkinson, in *U.S. Antarctic Program: Hearings Before the Subcommittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives*, 1 and 3 May 1979 (Government Printing Office, Washington, D.C., 1979), pp. 75–111.
112. Polar Group (D. J. Baker, Jr., *et al.*), *Rev. Geophys. Space Phys.*, in press.
113. I am most grateful for helpful comments from D. J. Baker, Jr., W. S. Benninghoff, C. R. Bentley, L. C. Bliss, C. Craddock, G. H. Denton, L. DeGoes, J. O. Fletcher, D. K. Grayson, R. A. Helliwell, T. Hughes, W. T. Hushen, J. M. Mitchell, Jr., D. Paulson, J. M. Rensberger, T. Scully, E. P. Todd, J. H. Zumberge, and two anonymous referees.