NSB-87-128

The Role of The National Science Foundation In Polar Regions

A REPORT TO THE NATIONAL SCIENCE BOARD

Committee on the NSF Role in Polar Regions
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NATIONAL SCIENCE BOARD
WASHINGTON, D.C. 20550

June 19, 1987

Dr. Roland W. Schmitt
Chairman
National Science Board
Washington, DC 20550

Dear Roland:

I am pleased to transmit to you the final report of the National Science Board Committee on the NSF Role in Polar Regions. In pursuing your charge to the Committee we have kept clearly in view the responsibility entrusted to the National Science Board to promote research in polar regions as well as other areas of the globe.

In this report we state our conviction that there is important research in the national interest to be done in both the Arctic and the Antarctic. The National Science Foundation must strengthen its leadership role as the agency responsible for the United States Antarctic Program and coordinator for basic research in the Arctic.

The Committee consulted widely across the Nation and within the National Science Foundation in the conduct of its business. At our meetings, public hearings, and field trips to Antarctica and the Arctic, we heard from leaders representing academic institutions, industry, federal, state and local government, professional societies and native peoples of the Arctic. There were also numerous interactions with members of the National Science Board and the NSF staff. The issues we dealt with are complex and interactive, with multiagency and international components. None of the issues are easily resolved. It will require carefully developed plans and sustained efforts in order for NSF to achieve its objectives within the polar regions.

I would like to thank the members of the Committee for the deep sense of responsibility and conscientiousness that they brought to this task. In addition, members of the NSF staff, especially the Polar Programs Division, were extraordinarily helpful and made significant contributions to our work.

We commend your foresight in establishing the Committee. We look forward to continued activity in reviewing the progress of NSF in accomplishing the recommendations of this report and assisting in that accomplishment wherever possible. The Committee is very hopeful that this report will trigger the necessary action that we urge through our recommendations. The report is meant to be widely distributed and we expect it to be made available to appropriate individuals and organizations.

Sincerely,

Rita R. Colwell

Rita R. Colwell
Chair, NSF Task Committee on the NSF Role in Polar Regions

Members of Committee:

Perry L. Adkisson
Warren J. Baker
Craig C. Black
K. June Lindstedt-Siva
Anton Inderbitzen, Executive Secretary
William J. Merrell, Jr., NSF Liaison

Resolution re Report of the NSB Task Committee on NSF's Role in Polar Regions

The National Science Board accepts the Report of the NSB Task Committee on NSF's Role in Polar Regions and thanks the Task Committee for its efforts. Further, the Board requests that the Director evaluate the report proposals and prepare a plan of action to respond to the report not later than March 1988. Furthermore, this report should be taken into consideration as the FY 1989 budget is formulated.

June 19, 1987

ACKNOWLEDGEMENTS

The Committee wishes to express its sincere appreciation to the staff of the National Science Foundation Science Board Office for their invaluable assistance in making this study and report possible. Special thanks go to Dr. William Merrell, Assistant Director for Geosciences, Dr. Peter Wilkniss, Director, Division of Polar Programs, Dr. Anton Inderbitzen, Executive Secretary for the Committee, and the entire staff of the Division of Polar Programs.

Special acknowledgement is also given to all of the participants at the meetings who provided material to the Committee. Their presentations represent the core of our study and this report. These include:

Dr. Thomas F. Albert, North Slope Borough, Alaska
Dr. Roger L. Arnoldy, University of New Hampshire
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Cmdr. Lawson Brigham, U.S. Coast Guard
Dr. Wallace Broecker, Columbia University
Dr. Jerry Brown, National Science Foundation
Dr. Ted E. DeLaca, National Science Foundation
Mr. James F. Devine, U.S. Geological Survey
Dr. Elliot C. Dick, University of Wisconsin
Dr. David H. Elliot, Ohio State University
Dr. Thomas R. Fink, ARCO Alaska, Corp.
Dr. William Fitzhugh, Smithsonian Institution
Dr. Sherman Garnett, Department of Defense
Dr. Arnold Gordon, Columbia University
Dr. Norman Hackerman, Robert A. Welsh Foundation
Dr. Albert A. Harrison, University of California, Davis
Mr. Richard Hayes, U.S. Coast Guard
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Dr. Raymond D. Watts, U.S. Geological Survey
Dr. Gunter Weller, University of Alaska
Dr. Peter E. Wilkniss, National Science Foundation
Dr. James H. Zumberge, University of Southern California

The Committee also wishes to express its genuine appreciation to all of the many people in Alaska and Antarctica that made our trips to these two polar regions so interesting, educational and successful.

Thank you all for making our task so enjoyable.

Rita R. Colwell
Chairman
NSB Committee on NSF's
Role in Polar Regions

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EXECUTIVE SUMMARY

Since 1970 the National Science Foundation (NSF) has had responsibility for the management of the U.S. Antarctic Program, including logistic support. Under the Arctic Research and Policy Act of 1984, the NSF was designated lead agency for implementation of the Act. These responsibilities, together with growing awareness of U.S. interests—strategic, environmental, economic, and scientific, among others—in the polar regions, led the National Science Board (NSB) to appoint a special committee, to examine the role of the NSF in polar regions. The Committee on the NSF Role in Polar Regions, chaired by Rita R. Colwell, was appointed in June 1986, and its report and recommendations were to be submitted to the Board in June 1987.

The Committee scheduled a series of meetings from September 1986 through February 1987 during which experts representing fields of polar research and organizations concerned with such research made oral presentations and provided additional written background material for committee consideration. Included in the Committee review were scientific needs and opportunities in meteorology and climate, ocean sciences, earth sciences, glaciology, upper atmosphere research and astronomy, biology and ecology, medicine and health, behavioral and social sciences, and engineering. In addition, the Committee considered the impact of international, national, and state policies and interests on the nature and conduct of polar research, as well as the implications of legal, environmental, and industrial concerns for polar science and engineering. Logistic requirements for effective U.S. research programs in the Arctic and Antarctic were examined, as were trends in the financial support of polar research.

Based on its detailed review, the Committee concluded that the NSF has an opportunity to integrate polar science into a broad, global systems-oriented program at the frontier of science, and that the Foundation should take additional actions necessary to fulfill its role as lead agency for basic scientific research in the polar regions. The Committee offers 15 specific recommendations to assist the NSF in fulfilling its primary responsibility for polar science and to strengthen U.S. research and presence in the polar regions. The general thrust of these recommendations is as follows:

1. Scientific needs and opportunities should determine the research conducted in both polar regions, with logistics deriving from and supporting the research rather than dictating it.
2. The NSF should establish and oversee the operation of a network of research support centers for the polar regions.
3. A logistics program should be established for the Arctic to support the NSF research projects and scientists in the northern polar regions.
4. The NSF should take the initiative in coordinating the development of an interagency national polar research plan, including both the Arctic and the Antarctic.
5. The NSB should encourage the National Institutes of Health and other appropriate agencies to support increased health and medical science research in polar regions, and NSF should, itself, support a related program of basic social sciences research in polar regions.
6. Research on the culture, history, linguistics, archaeology, and physical anthropology of arctic peoples should be established in the NSF as an identified and appropriately staffed program within the Division of Polar Programs.
7. A research vessel with icebreaking capability should be acquired for the U.S. Antarctic Program, and a research vessel capable of scientific and engineering research in arctic seas also should be acquired.
8. The cooperation of private organizations and industry should be sought in the construction of facilities and provision of logistic support in the Arctic and Antarctic.
9. The health, safety, and environmental protection practices for polar research programs, especially the U.S. Antarctic Program, should be studied and upgraded as necessary.
10. Systems for remote and automated data collection should be incorporated in the development of the recommended national plan for polar research (see #4 above), funded, and when in place, fully used.
11. The U.S. Navy's VXE-6 Squadron should remain an integral part of the U.S. Antarctic Program; however, the remaining support functions provided by the U.S. Naval Support Force Antarctica should be reviewed by NSF management for possible transfer to civilian contractors as sug-

gested by the U.S. Navy, if such transfer proves to be the most efficient and cost-effective option.

12. The NSF should take a stronger role in the development of polar policy.

13. Stronger recommendations concerning tourism and the responsibility for tourists should be made to the Treaty nations through the Antarctic Treaty Consultative Meetings. NSF should take a lead role in these international deliberations. In the United States, national legislation should be sought to ensure that tourists are properly insured or indemnified before they visit Antarctica, and nongovernmental groups should cooperate in the development of a voluntary responsible set of guidelines for tourism in the polar regions in general, and especially in the Antarctic.

14. Basic engineering research should be conducted in the polar regions, with development of the engineering knowledge required for operation in the polar environment a specially targeted objective.

15. Over the next 3 years, in addition to funding for the recommendations cited, core funding for polar research should be increased to a level twice that budgeted for Fiscal Year 1988.

INTRODUCTION

ORIGIN OF THE STUDY

Growing awareness that the polar regions are vital to a broad range of national interests—environmental, economic, strategic, scientific, and political, among others—has stimulated increasing attention in the public and private sectors to U.S. goals and activities in the Arctic and Antarctic. The National Science Foundation (NSF) has major mandated responsibilities in both regions, particularly in the Antarctic. In addition, a new initiative in the NSF Directorate of Geosciences, a comprehensive, multidisciplinary study of global change, is helping to define and strengthen the role of the NSF in polar regions.

Because of the increasing prominence of polar research and the NSF's related responsibilities, the Chairman of the NSF's National Science Board, Roland W. Schmitt, established a special committee in June 1986 to review the role of the NSF in polar regions and to prepare a report of its findings and recommendations for consideration by the Board in June 1987. The Committee was chaired by Rita R. Colwell, and its members were Perry L. Adkisson, Warren J. Baker, Craig C. Black, and K. June Lindstedt-Siva. The purpose of the study was to provide guidance to the Board in shaping the most effective programs to meet the opportunities in polar research and, thereby, to enhance the contributions of polar research to national objectives and scientific understanding. A basic requirement is to foster educational and career opportunities that will produce the needed scientific and engineering manpower and expertise.

The Committee held a series of meetings (August 13, September 19, October 16-17, November 12, and December 18, 1986; January 14 and February 18, 1987) at which experts from various fields of polar science and from organizations concerned with polar research made presentations. Topics included scientific needs and opportunities, logistic support, research policy, and trends in the support of research. Background papers and related material supplemented the oral presentations. The Committee then met several times in spring 1987 to organize its report and prepare its recommendations.

BACKGROUND

NSF Mandate

Following a study by the National Security Council in 1970, National Security Decision Memorandum 70 directed continuation of the U.S. Antarctic Program at a constant level of effort and the transfer of responsibility for the budgeting and management of the program to a single agency, the NSF. Subsequent studies in 1975 and 1980 reaffirmed the NSF role and led to White House Memorandum 6646 in 1982, which states that "The United States Antarctic Program shall be maintained at a level providing an active and influential presence in Antarctica designed to support the range of U.S. antarctic interests." It further states that the NSF should continue to "budget for and mange the entire United States national program in Antarctica, including logistic support activities so that the program may be managed as a single package; fund university research and federal agency programs related to Antarctica. . . ." A review by the Office of Management and Budget also reaffirmed the NSF role as a single agency program manager and resulted in a separate appropriation account for the U.S. Antarctic Program.

In 1969, the Vice President of the United States, as Chairman of the National Council on Marine Resources and Engineering Development, named the NSF as lead agency for the extension of arctic research. The NSF responded by establishing its Arctic Research Program in 1971 to coordinate and extend U.S. research efforts in the Arctic. However, the greatest impetus to a more active role for the NSF in the Arctic came with the passage of the Arctic Research and Policy Act of 1984 (P.L. 98-373). The Act created two new entities: a five-member Arctic Research Commission, with the Director of the NSF serving *ex officio*, to "develop and recommend an integrated national Arctic research policy . . . and assist in establishing a national Arctic research program plan to implement the Arctic research policy"; and an Interagency Arctic Research Policy Committee composed of representatives of federal agencies that have arctic research programs, with the NSF representative serving as chairman of this committee. The NSF was also designated as the responsible agency for implementing arctic research policy. Among the duties of the Interagency Committee are (a) surveying arctic research programs as a basis for determining priorities for future research; (b) working with the Commission to develop an integrated national arctic research policy; (c) developing, in consultation with the Commission, a 5-year plan to implement this policy; and (d) arranging for the preparation of a single multiagency budget request for arctic research.

Research in the Arctic and Antarctic

Differences between the Arctic and Antarctic influence the conduct of research in these regions. The Arctic is an ocean basin covered by ice and surrounded by land that has been populated since prehistoric times and that falls within the boundaries of a number of nations. In contrast, the Antarctic is a continent, 97 percent of which is covered with glacial ice averaging 7,000 feet in thickness. It has no indigenous human population and is separated from populated areas by an ocean known for its severe weather, continuous ice cover during much of the year, and extremely large icebergs.

A second difference is the political context in which polar research takes place in the Arctic and Antarctic. The Antarctic Treaty provides for peaceful uses of the antarctic continent and affords a framework for international cooperation in research. Although seven Treaty nations have claimed parts of Antarctica, these claims are not recognized by other nations and have been kept in abeyance by the provisions of the Treaty. Open access to all parts of the continent is also assured by the Treaty. Maintenance of "an active and influential [U.S.] presence" (White House Memorandum 6646, 1982) in Antarctica consists of the conduct of a high-quality scientific program in major fields—earth, glaciologic, atmospheric, oceanographic, ecological, and biomedical sciences (currently a total of 129 projects involving 335 people)—and provision of logistic support, including year-round operation of one interior and two coastal stations, as well as summer operation of additional field camps.

In the North, the situation is entirely different. Because the Arctic crosses national boundaries, national interests and sensitivities affect the planning and conduct of research and the exchange of information and data. Further, the Arctic is the site of national security installations, such as the Northern Warning System, and is rapidly becoming the most important base for seaborne strategic delivery systems and potentially for deployment of air-launched cruise missiles (Young, O. The Age of the Arctic. *Oceanus*, 29, (1), Spring 1986, 9-17). In addition to military activities, development and exploitation of renewable and nonrenewable resources introduce yet another broad set of issues and problems, such as environmental protection, resource management, land use, and conservation. An engineering and applied orientation has characterized arctic research, yet in many instances basic knowledge of physical and biological phenomena and processes is lacking. Research and long-term follow-up studies are required to solve or cope with these problems. In some cases, basic research in the Antarctic is also directly relevant; for example, upper-atmospheric phenomena that disrupt communications and surveillance systems are often best studied from the Antarctic or from corresponding points in the north and south polar regions.

A third and especially important difference that influences research is the presence in the Arctic of an indigenous human population. Over the past two decades, this population has been greatly augmented by new settlers and transient workers as resource exploration and industrial development have increased. The environmental, health, and socioeconomic concerns of the inhabitants of the Arctic shape much of the research taking place there. For example, indigenous peoples are seeking greater participation in the planning and management of research that affects them and in the management of resources on which their culture, lifestyle, and economic well-being depend. At times, national, industrial, and local interests come into conflict, as, for example, on issues of land use and impacts of development on wildlife and fish. Multidisciplinary, long-term, cooperative basic research often is needed for scientific progress and for resolution of such disputes as the current one about the possibility of opening lands within the Arctic National Wildlife Refuge to development. For many scientific problems international cooperation, which also can be difficult to achieve in the Arctic, is required to reach a solution. The recent agreement between the University of Alaska and the Siberian Branch of the U.S.S.R. Academy of Medical Sciences for a cooperative medical research program and sharing of data is a major breakthrough that will benefit residents of all northern circumpolar countries. The program also emphasizes the need to train native peoples to conduct such research rather than serving only as the subjects studied.

Global Change

Perhaps the broadest public awareness of the Arctic and Antarctic and of the importance of polar research has resulted from concern about environmental problems. The polar regions, major determinants of global climate, are especially sensitive to climatic change. Improved understanding of the interaction of arctic and antarctic atmospheric, oceanic, and terrestrial systems is basic to predicting, detecting, and attempting to cope with the impacts of climatic change, such as climatic warming as a result of increasing levels of atmospheric carbon dioxide. Questions that have received much recent public attention are the cause and significance of the seasonal decrease in stratospheric ozone detected over Antarctica during the past decade and the stability of the West Antarctic Ice Sheet, which could affect sea level and coastal habitation in the future. Data collected in Antarctica from August to October 1986 suggest that atmospheric chemistry, especially the buildup of chlorofluorocarbons, could be a factor, perhaps the main factor, in the ozone phenomenon.

The relationship of the polar regions to global environmental systems will tie NSF's future support for polar research closely to the new Global Geosciences Program in the Directorate of Geosciences. Specific emphases in the program will include: (a) reconstructing the history of global environmental change; (b) understanding contemporary change in the physical environment and in the biosphere; and (c) understanding major global biogeochemical and hydrologic cycles. The NSF's program will be coordinated with the International Geosphere-Biosphere Program, an international effort sponsored by the International Council of Scientific Unions. This global research program

> *symbolizes the realization that a complex industrial society is vulnerable to environmental change . . . that a comprehensive, global approach to understanding that change is better than* ad hoc *alarms over problems such as carbon dioxide buildup, ozone depletion, and acid rain"* (Science, *233, 5 September 1986, p. 1040).*

Clearly, research in the polar regions must play a crucial part in this international effort. For example:

- The polar ice contributes to understanding of climatic change through the unique record of past climates and atmospheric constituents that it provides.
- Antarctica is one of the seven major lithospheric plates and abuts four others. We need to understand this large part of the earth from the upper atmosphere to the base of the continent.
- The Arctic Ocean is the least investigated of the world's oceans, yet with its adjacent seas, it has major impact on the circulation and physical properties of the world ocean and contributes to climatic change.
- Biological research in both polar regions provides information about adaptations to extreme environments and contributes to the understanding of the origins and dispersal of flora and fauna.

ORGANIZATION OF THE REPORT

As noted in the proceeding section, the different political context in the Arctic and Antarctic affects the nature and conduct of research in these regions. Therefore, as background to its consideration of research needs and opportunities in polar science and engineering, the Committee looks briefly in the next chapter at research policy, from international, national, and state perspectives, and from industrial, legal, and environmental points of view.

The third chapter describes basic research opportunities in nine sets of disciplines: meteorology and climate, ocean sciences, earth sciences, glaciology, upper-atmosphere research and astronomy, biology and ecology, medicine and health, behavioral and social sciences, and engineering research. The content of this chapter is the foundation for the Committee's recommendations on research priorities, logistics, and funding.

Logistic support of polar research is the subject of the fourth chapter. Again, the Arctic and Antarctic present quite different problems. In the Antarctic everything pertaining to human habitation and the conduct of research must be brought to the continent, and the NSF has sole responsibility for provision of logistic support. In the Arctic, federal agencies, state and local organizations, industry, and academia are all engaged in research, and there is no central focus for logistic planning and support. Improved coordination, cooperation in the use of facilities and instrumentation, and increased funding are urgent needs.

In the final chapter, the Committee presents its conclusions and recommendations. The recommendations address basic research opportunities that the NSF should pursue, issues of logistic support, and the level of funding required to realize the potential of polar science and engineering research and to maximize the contributions of such research to national objectives in the Arctic and Antarctic.

The Appendix to the report lists the reports made to the Committee by those engaged in basic polar research and by those concerned with research policy, logistics, or support. Related reports, data, and publications considered by the Committee are also listed.

POLAR RESEARCH POLICY

Polar research takes place in a geopolitical context that significantly influences its substance, objectives, and effectiveness. A brief summary of research policy from international, national, state, and other (industrial, legal, and environmental) perspectives provides background for the consideration of recent activities and opportunities in polar research.

INTERNATIONAL CONSIDERATIONS

Following the cooperative scientific activities of the International Geophysical Year (IGY) in 1957-1958, during which 12 countries established some 60 research stations in Antarctica, the Antarctic Treaty came into force in 1961. It has formalized for 30 years the scientific cooperation and free access that had characterized the IGY and made that effort so productive. Key provisions of the Treaty included the following:

- Antarctica shall be used for peaceful purposes only . . . .
- Freedom of scientific investigation and cooperation shall continue.
- Scientific program plans, personnel, observations, and results shall be freely exchanged.
- Nuclear explosions and disposal of radioactive wastes are prohibited
- Treaty-state observers shall have free access—including aerial observation—to any area and may inspect all stations, installations, and equipment . . . .

There were 12 original signers, who became consultative parties to the Treaty and met regularly to discuss arrangements for scientific research, exchange of data, environmental preservation, and other issues of mutual concern. Other nations acceded to the Treaty, but consultative status—participation in decision making—was granted only when a nation established a permanent scientific station in Antarctica. Thus full participation in the Treaty system requires the demonstration of abiding interest through maintenance of an active scientific program.

The Scientific Committee on Antarctic Research (SCAR) of the International Council of Scientific Unions, established earlier than the Treaty ratification, is an outgrowth of the IGY. This nongovernmental body fosters scientific information exchange through meetings, symposia, and publications, responds to requests from Treaty nations for advice on scientific needs, and recommends to the Treaty nations research responsive to these and other needs, such as conservation. In regard to conservation, SCAR recommends the establishment of Sites of Special Scientific Interest and Specially Protected Areas. SCAR has a number of discipline-based working groups and issue-oriented groups of specialists that prepare reports and recommendations on particular fields of research or problems for consideration by SCAR and the Treaty nations. Research recommendations by SCAR, therefore, can lead to the scientific input that assists Treaty nations in the resolution of political issues.

In recent years, antarctic mineral resource potential, an increase in commercial fisheries, and Law of the Sea negotiations have increased international awareness of Antarctica, led to new agreements and conventions under the Treaty, and stimulated a number of nations to seek participation in SCAR and in the deliberations of the Treaty nations. The Treaty is subject to review in 1991. A question is how effective the Treaty system would continue to be should the criteria for active participation be modified at that time and the number of consultative parties substantially increased.

U.S. political interests in Antarctica center on strengthening the Treaty, thereby preserving Antarctica as a zone of peace, reserved for international scientific cooperation, with continuing U.S. access to all of Antarctica. From an environmental and scientific perspective, U.S. interests include improved understanding of (a) the antarctic continent and adjacent marine areas, (b) phenomena and interactions that are unique to Antarctica or can best be studied there, and (c) the relationship of antarctic phenomena and processes to global systems. The United States is also interested in conservation of living resources of the continent and the Southern Ocean through effective implementation of the Convention on Conservation of Antarctic Marine Living Resources and in the development of an agreed-upon system for dealing with possible future mineral resource exploration and exploitation in Antarctica. Further, should such resource-related activities become acceptable, U.S. interest would focus on ensuring continued nondiscriminatory access to all parts of the continent.

The principal means by which the United States Government endeavors to strengthen the Antarctic Treaty and to further its continuation are maintenance of key stations, unique logistics, a scientific program of highest quality, and leadership in international cooperative research and policy-related activities. Thus, the operation and results of the U.S. Antarctic Program are directly linked to U.S. political interests and objectives in the Antarctic. This has been made explicit in policy memoranda (e.g., White House Memorandum 6646, in 1982) in which U.S. commitment to a leading role in Antarctica has been repeatedly emphasized, with such leadership defined as the conduct of scientific research in and around the continent and participation in the system of international cooperation pursuant to the Antarctic Treaty.

In the north polar regions, the United States is but one of a number of arctic-rim nations. A significant portion of the State of Alaska falls within the area variously defined as the Arctic. Although research in the Arctic is not new, it has accelerated in the United States and other arctic-rim nations with the development of resources and with the growing strategic importance of the area. Bilateral and multilateral governmental and nongovernmental agreements have proliferated, as have international organizations concerned with arctic research. A partial list compiled by the Arctic Research Commission in April 1986 shows 18 bilateral and 6 multilateral U.S. Government agreements in scientific research; 18 bilateral and 19 multilateral nongovernmental scientific research programs; and 140 organizations, concerned at least in part with arctic research, in individual countries. Fifty-three of these organizations are in the United States. (See "Arctic Cooperative Research Agreements and Major Arctic-Rim Research Organizations. Initial Compilation." Arctic Research Commission, Los Angeles, California, 1986, pp. 1-7.)

A number of international organizations have attempted to improve and facilitate cooperation in arctic research with varying degrees of success. Their existence attests to the need for more effective means of achieving international cooperation and the exchange of data and research results. Although such cooperation is fundamental to the solution of many scientific, environmental, and biomedical questions, and although some productive cooperative arrangements have developed in these fields (most recently, the University of Alaska-Siberian Medical Research Program), issues of national security, national boundaries, and resource exploitation complicate the international picture in the Arctic. Policy tends to evolve on a case by case basis to deal with specific research opportunities and problems. Strengthening international cooperation in arctic research is a concern of both the Interagency Arctic Research Policy Committee and the Arctic Research Commission.

NATIONAL CONSIDERATIONS

In the Antarctic, international and national interests are closely linked. Scientific excellence and leadership in international cooperative activities related to the Antarctic Treaty are the means by which the United States maintains "an active and influential U.S. presence," as called for in U.S. policy, and strengthens the Treaty that ensures peaceful use of and open access to the antarctic continent.

The most recent U.S. policy statement on the Antarctic (White House Memorandum 6466, 1982) indicates that other federal agencies may undertake directed, short-term scientific activities in the Antarctic on the recommendation of the Antarctic Policy Group, subject to budget review and coordination with the NSF on logistics. The Division of Polar Programs (DPP) has responded by issuing a U.S. Antarctic Program Directive dealing with other agency participation.

Other agencies can contribute to research and the acquisition of needed data in the Antarctic, and some of them wish to undertake such programs. For example, the U.S. Geological Survey has pointed out that the "directed short-term research" stipulated in the 1982 policy does not meet the long-term needs in earth sciences, and that the directive to the NSF to fund university and federal agency research in the Antarctic puts federal agencies in competition with academic institutions for funds. Complementary federal and university-based efforts have been urged. The NSF could take the lead in exploring ways that other agencies might contribute to and strengthen the U.S. program in Antarctica. For example, behavioral and social science research, engineering research, and transportation research have received no sustained attention in the U.S. Antarctic Program, and medical research has played but a small part in the overall research effort. There is need for basic and applied science and mission agencies whose mandate is broader than basic science can contribute, as, for example, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS) have done in various data collection and monitoring programs. Both NASA and NOAA worked with the NSF on the 1986 study of the "ozone hole" in the stratosphere over Antarctica. (See also Watts, R.D., Comments to the Committee on the Role of NSF in Polar Science, presentation to the Committee on December 18, 1986; and Kimball, L., Policy Impact on Polar Environmental Issues, presentation to the Committee on December 18, 1986.)

The Arctic Research and Policy Act of 1984 (P.L. 98-373) was a major step toward better definition of roles and responsibilities in the Arctic. The Act identifies a broad range of issues and problems that require scientific and engineering research if U.S. objectives in the Arctic are to be met. These include national defense, management of renewable and nonrenewable resources, environmental protection, conservation, effective transportation and communication systems, amelioration of natural hazards and pollution, understanding of global climate and weather, enhancement of health and quality of life, and taking advantage of the opportunities offered by the Arctic as a natural laboratory. The intents of the Act were to establish national research policy, goals, and priorities in the Arctic and to provide for the development of a comprehensive plan of basic and applied research to implement the policy.

The Act established the Arctic Research Commission (representing academia, industry, and indigenous inhabitants) and the Interagency Arctic Research Policy Committee (composed of representatives of federal agencies, with the NSF representative as chairman). It also assigned the NSF responsibility for implementing arctic research policy. The Commission's assigned tasks include recommending a national arctic research policy, cooperating with the Interagency Committee in developing a 5-year arctic research plan to implement the policy, fostering cooperation among federal, state, and local governments in arctic research, and recommending ways to improve logistic support and data management. The Interagency Committee is responsible for conducting a survey of arctic research activities, working with the Commission to formulate arctic research policy and a plan to implement it, providing the necessary coordination and data for the preparation of a single, integrated budget request for arctic research, and improving coordination among federal agencies engaged in arctic research. The Commission reports annually to the President and the Congress; the Interagency Committee, biennially.

An arctic research policy has been developed and adopted. It opens with the statement that "It is in the national interest of the United States to support scientific and engineering research . . . to implement its national policy of protecting essential security interests in the Arctic, promoting rational development in the arctic region while minimizing adverse environmental effects, and contributing to the knowledge of the Arctic environment or of aspects of science that are most advantageously studied in the Arctic." Research priorities have been recommended, and through a series of workshops organized by the Interagency Committee staff, the *U.S. Arctic Research Plan* was developed. On March 23, 1987, the Interagency Committee approved the plan, which was transmitted to the President on June 25, 1987, and to the Congress thereafter.

The Act provides an opportunity for the NSF to exercise leadership in the planning, coordination, and implementation of U.S. scientific and engineering research in the Arctic, and the agency has responded.

THE STATE PERSPECTIVE

The U.S. Arctic, as defined in the Arctic Research and Policy Act, includes approximately half the State of Alaska, as well as the Bering, Chukchi, and Beaufort Seas. About 30,000 people, most of whom are indigenous, live in this area. Many, until recently, followed a subsistence lifestyle; some still do. All have close ties to the ocean, the land, and the wildlife and are concerned about the environmental impacts of industrial development and government regulatory policies that affect subsistence hunting.

As federal research activities in the Arctic proliferated during the 1970s and early 1980s, the local inhabitants saw little coherence in the effort and had little voice in what was taking place. From their point of view, billions of dollars were flowing from the Arctic through the exploitation of nonrenewable and renewable resources, but little attention was given to the impacts of development on human populations and on the environment or to the needs and priorities of Native Alaskans. As a result, local groups began to seek technical advice, to organize research of their own to meet needs ignored by federal research programs, and to seek a voice in the formulation of arctic research policy.

In an address to the State Legislature in January 1986, then-Governor Bill Sheffield affirmed Alaska's "commitment to science and engineering research efforts . . . within the state to help understand phenomena, solve its problems, develop its economy, and improve the quality of life of its citizens." Subsequently, an act establishing the Alaska Research Policy was passed by the legislature and signed into law in May 1986.

The commitment to scientific and engineering research is strong not only at the state level but at the local level as well. For example, the mayor of the North Slope Borough has a Science Advisory Committee, and many people in decision-making positions in the Borough government and in the Arctic Slope Regional Corporation have some familiarity with scientific and engineering research and a positive view of the contributions research can make to the solution of environmental, resource, health, and social problems. This awareness of the need for and benefits of research is in no small measure the result of the former Naval Arctic Research Laboratory, which gave many of the local people an opportunity to work with scientists in the field, provided continuity and focus to some of the U.S. research conducted in the Arctic, and fostered public awareness of and positive attitudes toward science.

Representatives of the North Slope Borough reviewed a preliminary draft of the *U.S. Arctic Research Plan*. Among their principal recommendations were the following:

- Native residents of Alaska should have a part in designing and implementing arctic research projects that affect marine and land-based ecosystems and in decisions on managing these ecosystems.

- The cultural, social, economic, political, and health concerns of the local people should rank second only to national defense in priority for arctic research and should be integrated into all aspects of the 5-year plan.

- Regional arctic research centers should be established for the conduct of research, logistic support, and direct involvement of arctic residents in the flow of scientific and technical information to and from the research community. (See "Development of a

Program to Provide for Review and Comment by U.S. Arctic Residents on the Design and Implementation of the Five-Year Plan of the Arctic Research and Policy Act. A Workshop held in Barrow, Alaska, October 22-23, 1986." North Slope Borough, Barrow, Alaska, December 2, 1986.) These recommendations received careful consideration in the development of the final draft of the *U.S. Arctic Research Plan.*

AN INDUSTRIAL PERSPECTIVE

From an industrial viewpoint, key questions in the Arctic are the following:

- What is the national importance of energy resources in the Arctic?
- What is the present capability to find arctic energy and mineral resources, and what new technology is needed to develop them?
- What is a meaningful balance between the national need for resources and the environmental concerns of inhabitants?

The nature and direction of much of the research conducted in the Arctic depends on the answers.

Because of the current recession in the oil industry, industrial research in the Arctic has decreased. However, there is opportunity to look ahead to the next surge of production and to anticipate some of the problems and the research needed to solve them. Many of these problems relate to land use and wildlife management. Assumptions about wildlife needs and impacts on migration patterns often are based on data and experience in the lower 48 states where farming and settlement disrupt habitats more frequently.

The assumptions may not apply in the more open areas of arctic Alaska. Research is needed to determine, for example, how much of the tundra wetlands is required to maintain populations of waterfowl; and whether fluctuations in populations are the result of changes in tundra habitat or in other areas along the migration route; whether pipelines impede caribou migration (figure 1); and what effects gravel causeways, barriers, and currents have on fish migration and productivity.

Other research needs are in the behavioral and social sciences, fields that have received little attention in the Arctic. Some suggested studies include investigations of psychosocial adjustments that occur after living and working for long intervals in isolated camps, impacts of long cycles of light and darkness and of extreme cold on productivity and personality, the transition among indigenous peoples from a subsistence lifestyle to a cash economy over a short period, and the physiological and culture adaptations of indigenous peoples.

Some of the greatest needs, from the industrial viewpoint, are materials research and engineering research (particularly in relation to icing of structures), impacts of sea ice on offshore structures, and ice hazards to transportation. Materials research has been relatively neglected. There has been insufficient research on how extreme cold affects building materials, lubricants, nonbrittle alloys, composite materials, and even concrete. Many fundamental problems in polymer chemistry in cold environments have yet to be solved.

Industry and government have different but complementary roles in arctic research; there is need and opportunity for cooperation. From the perspective of industry, the fundamental role of the Federal Government should be to establish comprehensive, interdisciplinary programs to understand the dynamics of arctic systems and to develop broad-scale data bases and long-term ecological monitoring programs, for example, creation and maintenance of a U.S. arctic satellite-derived ice data base. Research of regional or global scope should be the responsibility of the federal government. Of particular importance are climate modeling and improved short-term weather forecasting. Accurate forecasts are essential for users in the public and private sectors.

The petroleum industry views its role as attempting to understand the nature and interaction of localized phenomena and to develop advanced methods for safe, economic onshore and offshore exploration and development, with minimal environmental impact. Industrial research, therefore, centers on specific sites, operations, and problems, for example, ice gouging related to pipeline installation or ice characteristics and variability in relation to industrial structures or operations.

Because of the dominant effect of the physical environment on human activities in the Arctic, the needs for basic understanding and for developing the means to live and work effectively often overlap. There is opportunity for cooperative research to meet both scientific and engineering needs. Government and industry have cooperated in a number of programs: for example, multiyear studies of ice characteristics and variability, design studies for tankers, and whale ecology studies. The so-called "synthesis meeting," held in connection with the Outer

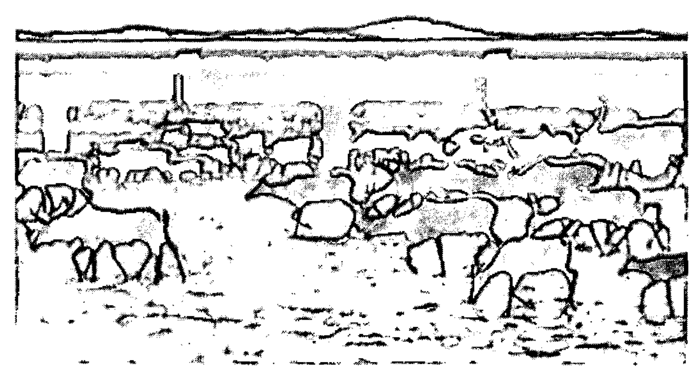

Figure 1. Caribou near pipeline. (Courtesy Arco Alaska)

Continental Shelf Environmental Assessment Program, also provided a useful exchange of information and experience between governmental and industrial researchers concerned with assessing hazards and environmental impacts of offshore operations. Innovative approaches and interdisciplinary, interorganizational cooperation are necessary to address many research needs. As lead agency for implementation of U.S. research policy in the Arctic, the NSF has an opportunity to stimulate and foster such cooperation in, for example, research on:

- physical properties and dynamics of sea ice
- characteristics and distribution of terrestrial and subsea permafrost
- basic structure and function of marine and terrestrial ecosystems as a basis for assessment and mitigation of environmental impacts.

A LEGAL PERSPECTIVE

With increasing research activity in the Antarctic and year-round occupation of research stations in this high-risk environment, the likelihood of legal problems increases. The extraterritorial application of U.S. law to antarctic activities and claims is being explored. A review of applications of law—for example, the Antarctic Conservation Act, the Comprehensive Crime Control Act of 1984, and a tax court decision holding that Antarctica is not a foreign country—was prepared for the Committee by C. Stovitz (The Development and Application of American Law to the Antarctic Program and to Expeditionary Forces, presentation to the Committee on December 18, 1986).

As the agency with responsibility for the U.S. program in the Antarctic, the NSF should consider the potential legal problems, the need for guidelines and methodology for the application of U.S. law in the Antarctic, and the need for awareness and clarification of legal issues. Twelve recommendations presented for Committee consideration (Stovitz, C. Presentation to the Committee on December 18, 1986) represent an attempt to stimulate the NSF to give attention to ways to ensure the rights and protection of the individual under law in the environmental circumstances of Antarctica. The general thrust of the recommendations was that the NSF should:

- determine NSF policy and position on legal issues that have arisen
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- inform participants in the U.S. Antarctic Program of the authority of the NSF and its position on legal issues and review contractual arrangements with participants, contractors, and foreign nationals
- plan for and create systems to handle possible criminal acts
- redefine the antarctic research program and its participants as an expeditionary force subject to special and unique applications of the law.

AN ENVIRONMENTAL PERSPECTIVE

Preservation of the relatively pristine environment of the Antarctic is a continuing concern of the Antarctic Treaty nations. Establishment of protected areas, conservation of marine living resources, implementation of environmental impact assessment procedures, and development of a regime to guide future mineral resource activities are among the ongoing efforts. The basic research and data collection that the NSF supports through the antarctic program provides information essential to decisions on environmental issues and conservation. The International Institute for Environment and Development has suggested that the NSF might take the lead and set an example among Treaty nations by incorporating into its program a component specifically directed toward acquisition of the data needed to establish environmental policy, particularly in regard to resource management. In addition, the U.S. Antarctic Program should enhance its role as a model to other nations in complying with Antarctic Treaty measures, such as distribution of environmental impact statements for information and comment and the maintenance of strict standards to protect the environment at antarctic research stations. Improved cooperation with SCAR in its efforts to provide advice to Treaty nations would also help to foster sound environmental policies. These and other actions were the subjects of ten recommendations submitted by the International Institute for Environment and Development (Kimball, L. Policy Impact on Polar Environmental Issues, presentation to the Committee on December 18, 1986) for consideration by the NSF. Among the principal recommendations were that the DPP should:

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- take the lead in applying and improving practices for the protection of the antarctic environment at its stations and field camps.

From a global environmental perspective, phenomena such as the seasonal decrease in ozone over Antarctica (figure 2), the increasing levels of carbon dioxide (figure 3) and chlorofluorocarbons in the atmosphere, and the change that is occurring in climate have stimulated growing concern in this and other countries. The need to understand what is taking place and to predict the rate and impacts of climatic change is urgent. The polar re-

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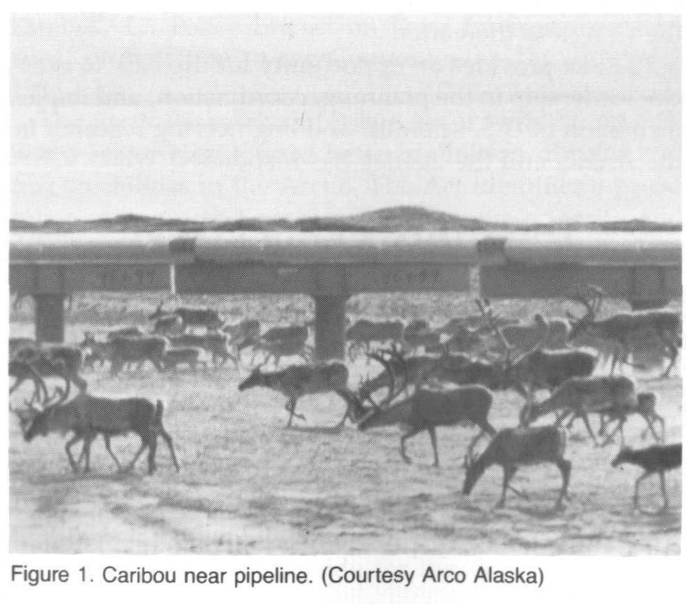

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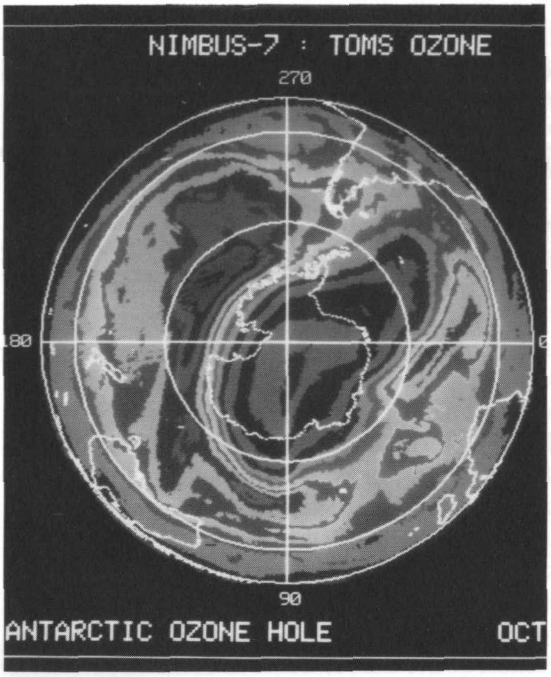

Figure 2. Ozone over the Southern Hemisphere, as mapped on October 10, 1986, by the total ozone mapping spectrometer (TOMS) aboard the Nimbus-7 satellite. (Image courtesy of A.J. Krueger, Goddard Space Flight Center, NASA.)

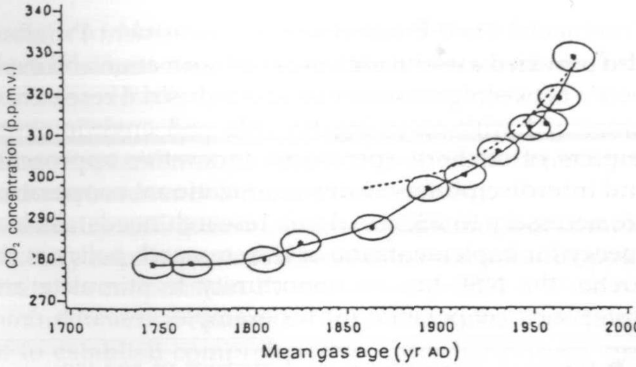

Figure 3. The growth of the atmospheric CO_2 concentration. The full curve (with ellipses showing the date and concentration uncertainties) has been derived from an ice core obtained at Siple, Antarctica. The broken curve is a backward extrapolation of the measurements that started in the 1950s, with estimated earlier figures for fossil fuel consumption. The difference of the two curves represents a biosphere input of CO_2. (Neftel, Moor, Oeschger, and Staufer, in *Nature*, 315 (45), 1985.)

gions might provide the earliest indications of global warming, and their ecosystems might be most affected. Further, the contributions of air-sea-ice interactions in polar regions to the global climate system hold the keys to understanding and predicting climatic change (figure 4). For these reasons, in particular, polar research merits a higher place among national priorities than it has previously been accorded (Topping, J.D., Jr. Policy Implications of Polar Research and Climate Change, presentation to the Committee on December 18, 1986).

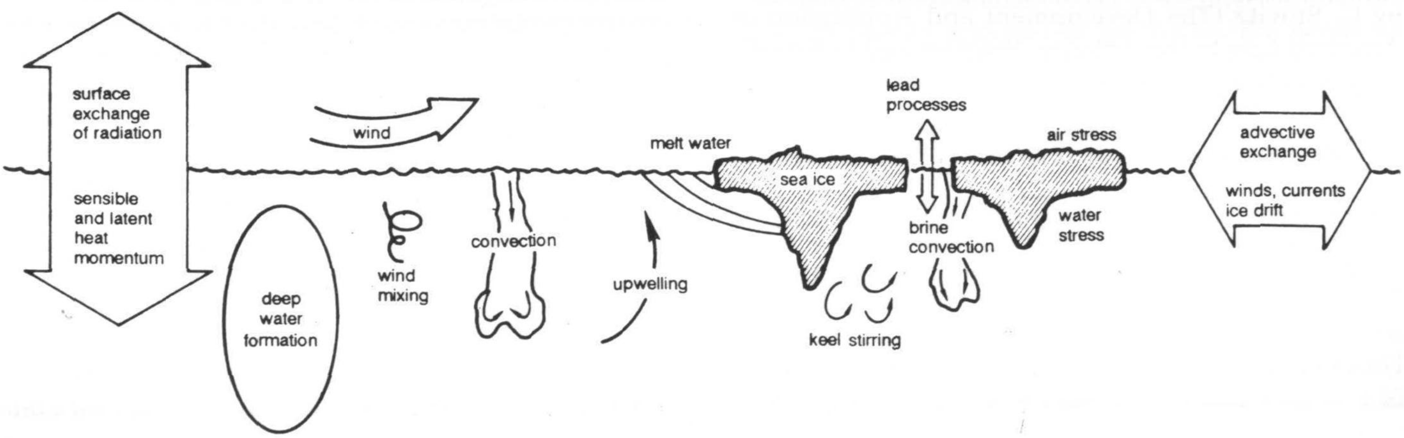

Figure 4. Schematic depiction of processes occurring at the air-sea-ice interface and affecting the structure of the ocean. (Arctic Ocean Sciences Board, *Greenland Sea Project*, National Academy Press, Washington, D.C., 1987)

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OPPORTUNITIES IN POLAR RESEARCH

Presentations made to the Committee by scientists engaged in basic polar research, additional written material they provided, and related reports are the sources for this chapter. It describes briefly the kinds of basic research conducted in the polar regions and the relevance of such research to many scientific and environmental problems. It also deals with research needs and suggested priorities that will shape the future direction of polar research, as well as with the general thrust of the research supported by the NSF's Division of Polar Programs (DPP). The chapter does not provide a comprehensive review of polar research. Other reports, for example, the "Polar Research—A Strategy" series issued by the Polar Research Board of the National Research Council, present in-depth assessments of the various fields of polar research. In the Arctic, the *U.S. Arctic Research Plan,* prepared by the Interagency Arctic Research Policy Committee, summarizes research supported by federal agencies, identifies needs, and recommends responsive programs. The intent here is to highlight some of the principal basic research opportunities that the Committee considered in arriving at its recommendations on the NSF's role as (a) lead agency for arctic research planning and for implementation of arctic research policy, and (b) manager of the U.S. Antarctic Program, including the provision of logistic support.

The boundaries between the nine discipline-based sections in this chapter are not sharply defined. Increasingly, an interdisciplinary approach to polar research is essential to the solution of scientific, engineering, and environmental problems, as well as to maximizing the cost effectiveness of research. Consequently, research opportunities in one discipline-based section are often directly related to those in another. The polar regions might best be regarded as research centers—geographic areas in which there are special opportunities to study the interrelationships among terrestrial, oceanic, atmospheric, and biological phenomena and processes.

METEOROLOGY AND CLIMATE*

Atmospheric processes not only influence climate on many time scales but also cause the deposition of snow and ice, influence ocean circulation and the extent of sea ice, carry pollutants, and cause storm surges and other catastrophic events. A better understanding of the dynamics and composition of the atmosphere is essential to improved weather prediction, amelioration of such problems as arctic haze and acid rain, and prediction of climatic change in relation to such phenomena as, for example, stratospheric ozone depletion and increasing levels of atmospheric carbon dioxide.

The Arctic and Antarctic are heat sinks in the global heat exchange system (figure 5), and their temporal variability directly affects weather and climate. The polar regions are also crucial in detecting changes in climate, for the variations within the atmosphere and oceans are large and directly affect sea ice and thus albedo. While ice and snow are extremely sensitive to variations in climate, changes in the amount and deposition of ice and snow further affect and change the climate system. In both polar regions, variations in the extent of sea ice affect the flow of heat from the oceans to the polar atmosphere, and, in the Antarctic, influence the atmospheric circulation over the ice sheet and modify the effectiveness of this continent as a global heat sink. Changes in snow cover affect the seasonal variations and survival of sea ice. These polar processes result in fluctuations of atmospheric and oceanic conditions in other parts of the earth; therefore, an understanding of the global climate system requires quantitative understanding of interactions among atmosphere, oceans, and ice masses in polar regions and of the way that interactions in the Arctic differ from those in the Antarctic. Consequently, the

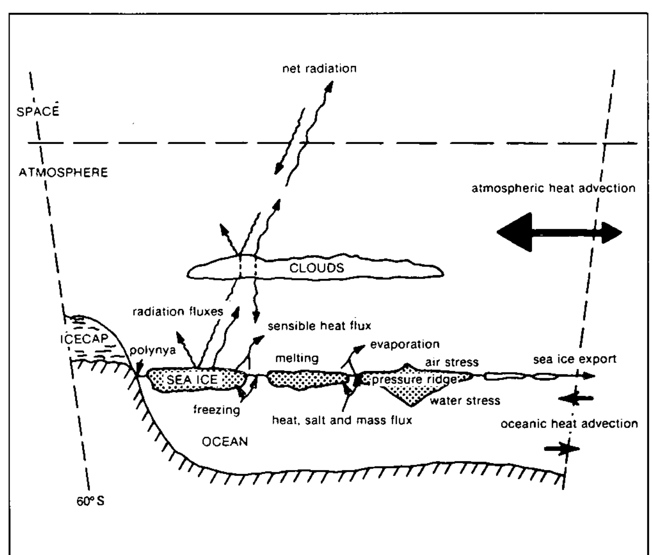

Figure 5. Heat budget processes. A model of the pack-ice zone in the Southern Ocean depicts the basic mechanisms controlling sea-air-ice interactions in the polar oceans. (Source: N. Untersteiner in *MOSAIC*, 9 (5), September/October 1978.)

*Including atmospheric chemistry.

Polar Research Board concluded in a 1984 report (*The Polar Regions and Climatic Change*) that two principal thrusts for research on climate should be:

> *The development of models of the global climate system, with special attention to improved simulation of climatic processes in the polar regions, and*
>
> *Better understanding of the global-scale response of the oceans to atmospheric changes in polar and subpolar latitudes. (p. 2)*

Scientific opportunities in atmospheric sciences and climate can be grouped roughly by time scale, from short-term (daily) variability to long-term climatic trends. Of the short-term phenomena, polar lows are among the priorities recommended for research in the *U.S. Arctic Research Plan* and by the Polar Research Board (*National Issues and Research Priorities for the Arctic*, 1985). These intense, mesoscale, low-pressure systems develop rapidly, almost explosively, in the North Atlantic and, less frequently, in the extreme North Pacific. The development of polar lows seems to be directly related to the position of the ice margin, for they strengthen rapidly as the system moves from an ice-covered region to a warmer surface of the open ocean. They differ from cyclones in size (about 100 kilometers compared to 1,000 kilometers) and in their southward trajectories and often go undetected in meteorological analyses and forecasts. They are characterized by strong winds and typically hit land along the North Atlantic coasts of Europe and on the U.S. North Pacific coast, severely damaging offshore and coastal areas. High-resolution satellite imagery, advances in regional-scale modeling, and field data from the marginal ice zone make research on polar lows timely.

On a somewhat longer time scale, interannual variability in the Arctic is great, but the reasons for the fluctuations are not fully understood. Atmospheric circulation and ice cover (figure 6), on time scales of months to seasons, show marked differences from one year to the next. For example, multiyear sea ice concentration was approximately 40 percent less in January 1981 than in January 1979, and the low-level arctic atmospheric circulation field recorded in June 1981 was the opposite of that recorded in June 1983. Meteorologists do not as yet understand the causes of such "flip flops" and cannot predict them. Studies suggest that variability of the sea ice and ocean results from atmospheric variability. Large-scale atmospheric circulation patterns determine the pattern of surface winds, which, in turn, affects ice motion, temperature, and ocean surface. Improved numerical models could provide the key to understanding the complex interaction of atmosphere, ocean, and ice, a priority emphasized by the Arctic Research Commission, the *U.S. Arctic Research Plan*, and the Polar Research Board (*National Issues and Research Priorities for the Arctic*, 1985). The models will require data—for example, on ice thickness, thermal fluxes, radiative fluxes, and the like—to improve and verify simulations.

Long-range prediction—monthly and seasonal forecasting—is a particular need in arctic meteorology, especially as industrial and military activity in the Arctic increase. Improved models and the application of some of the statistical techniques developed for lower latitudes could advance this field.

On the climatic time scale, a major focus of research is the high-latitude North Atlantic, the region of the largest air-sea heat exchange in the Northern Hemisphere. With the possible exception of the North Pacific, no region of the Northern Hemisphere has greater interannual variability of the atmospheric circulation. The interannual variability of North Atlantic sea ice is large, as previously noted, and the Greenland Sea/North Atlantic area is the primary region of mass and energy exchange between the Arctic Ocean and the global oceans. Further, the high-latitude North Atlantic and its peripheral seas are the regions of formation of much of the deep water of the world's ocean (figure 7). The processes in the high-latitude North Atlantic could be major causes of climatic changes that take place on a scale of decades to centuries. Evidence comes from analyses of ice cores drilled in the Greenland Ice Sheet, which show that glacial era climatic changes occurred in sharp jumps and that these shifts were accompanied by changes in concentrations of atmospheric constituents, including carbon dioxide and dust, and changes in temperature, precipitation, and ocean circulation (Broecker, W.S., D.M. Peteet, and D. Rind. Does the Ocean-Atmosphere System Have More than One Stable Mode of Operation? *Nature*, 315 2 May 1985, pp. 21-25).

North Atlantic deep water, which usually forms at the end of winter, is the main vehicle for exchange of heat, carbon dioxide, nutrients, and other substances between the deep ocean and the surface layers of the atmosphere. Changes in deep water formation affect climate, atmospheric carbon dioxide, and marine biological productivity. Because the Arctic Ocean is one of the sources of

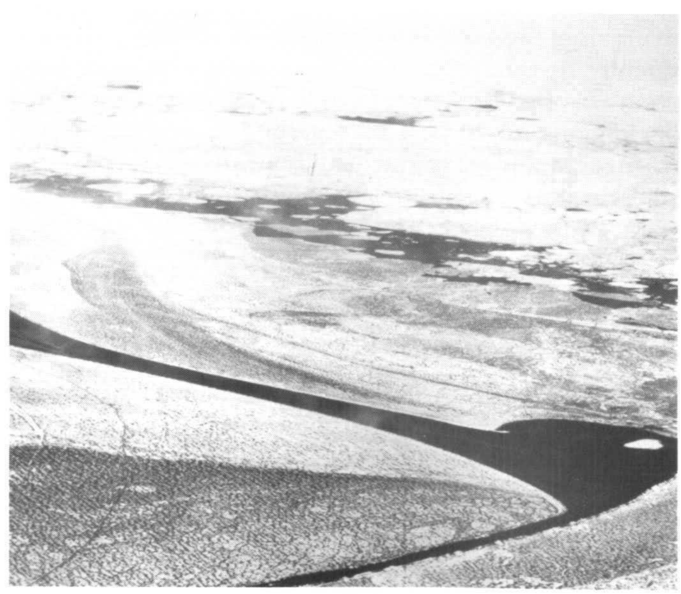

Figure 6. Ice cover on the Arctic Ocean.

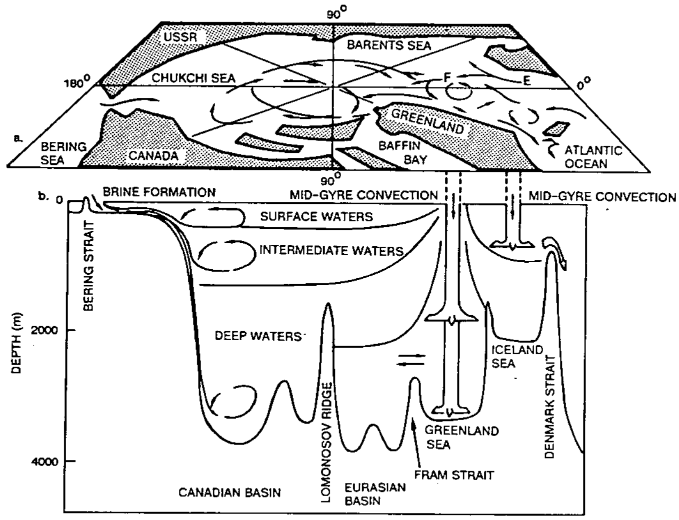

Figure 7. Schematic circulation and oceanic structure in the Arctic Basin and its adjacent seas. Relatively warm water carried northward with the Norwegian Atlantic Current (arrows marked E) and West Spitsbergen Current (arrows marked F) are cooled and thus sink and spread at intermediate depths both into the Arctic Basin and into the Greenland and Iceland gyres. Mid-gyre convection in these gyres produces dense water masses, which then spread throughout the region and into the remainder of the world ocean. (Source: Arctic Ocean Sciences Board, *Greenland Sea Project*, National Academy Press, Washington, D.C., 1987, p. 10; and Aagaard, K., J.H. Swift, E.C. Carmack, Thermohaline Circulation of the Arctic Mediterranean Seas. *Journal of Geophysical Research*, 90 (C5), 1985, pp. 4833-4846.)

the North Atlantic deep water, and because formation rates of North Atlantic deep water depend on interactions of the atmosphere, ocean, and ice in the marginal ice zone, systematic observations and a long-term monitoring program in the high-latitude North Atlantic are high priorities. Remote sensing systems on satellites and subsurface observing systems, together with data from ocean bottom and ice cores and hydrographic measurements from ships, should provide a detailed picture and lead to improved models for predicting variability in climate. The Arctic Research Commission, Interagency Arctic Research Policy Committee, and Polar Research Board have emphasized the need for such research.

An issue of particular concern is how climate will be affected by increasing atmospheric concentrations of carbon dioxide and other radiatively active trace gases. Model simulations suggest that the extent, temperature, and reflectivity of sea ice influence the extent of global warming, especially at high latitudes. Although models of arctic ice conditions are improving, those for the Antarctic are not adequate. The Antarctic is of particular concern because of the possible impact of climatic warming on the West Antarctic Ice Sheet and the changes in sea level that would result if it melted.

Ice cores from the Antarctic provide information not only about past climates of this continent but also about past climates worldwide. Like cores from Greenland, they yield data on atmospheric constituents, the timing of northern and southern glaciations, and the response of ice to atmospheric and oceanic conditions. Precipitation rates, temperatures, atmospheric chemistry, and volcanic, cosmic, and other fallout can be studied by analyzing ice cores. These, together with cores taken from ocean bottom sediments and from bogs, provide the data necessary to achieve a better understanding of climate.

In antarctic research five questions to improve understanding of global climate are the following:

- What record of climatic and environmental conditions during the last several 100,000 years is preserved in the antarctic ice sheets?
- What quantitative effects do variations in the atmospheric heat budget over the antarctic continent produce?
- How is the heat loss from Antarctica balanced by meridional transfers and mixing in the atmosphere and ocean?
- What effect does the Southern Ocean and the atmospheric processes of transport and transformation in the Southern Hemisphere have on the concentration and distribution of radiatively active gases in the atmosphere?
- How are the configuration and dynamics of the antarctic ice sheets controlled by its boundary conditions, particularly basal melting, surface temperature, and precipitation? (See Polar Research Board, *Research Emphases for the U.S. Antarctic Program*, 1983).

Further research also is needed on local phenomena including katabatic winds, oases, and polynyas, along with their effect on local climate and improved weather forecasting. Data from year-round, automatic weather stations have been useful in such studies.

Two atmospheric phenomena, arctic haze and the "ozone hole" over Antarctica, are currently receiving much attention. Arctic haze (a large-scale air pollution phenomenon that seasonally covers the Arctic Basin) was the focus of a multi-agency and multi-national airborne research effort—the Arctic Gas and Aerosol Sampling Program. Participants from agencies in the United States, Canada, Norway, Sweden, Denmark, and the Federal Republic of Germany cooperated during two field studies in March and April 1983 and 1986. Preliminary results indicate that manmade pollutants occur in layers interspersed with clean air throughout the troposphere in winter and spring. The haze layers consist of carbon, sulfur, and a variety of trace metals and organic chemicals. The black carbon in the haze absorbs solar energy at rates that suggest that haze layers might be warmed as much as 1°C per day, but the effects of haze on the radiation balance, climate, and cloud microphysics are still largely uncertain and need further study. The haze studied in 1983 was traced to industrial sites in the Soviet Union; it traveled to Spitzbergen in about 2 to 4 days and reached Alaska in about 5 to 9 days.

The U.S. Arctic Research Plan recommends that the United States and other nations conduct periodic studies of the arctic troposphere to understand atmospheric transport and the occurrence and impacts of anthropogenic airborne pollutants in the Arctic. It also calls for stations across the U.S. Arctic and the Yukon Basin to acquire data on air quality, atmospheric transport of pollutants, and climatic trends. The Polar Research Board recommended studies of sources, transport pathways, atmospheric chemical constituents, conversion processes, and effects on climate and on acidity of lake and tundra wetlands (*National Issues and Research Priorities in the Arctic*, 1985).

A report in the June 19, 1986, issue of *Nature* (Tuck, A.F., Depletion of Antarctic Ozone. *Nature*, 321, 1986, 729-730) states that:

> *The total amount of ozone overhead in late winter and early spring at Antarctica has decreased by about 40 percent during the past decade. Recent analysis of satellite data shows that the . . . abundances are among the lowest recorded anywhere on the globe. . . . A time series of ozonesonde profiles taken in 1982, when compared with data taken in the late 1960s and early 1970s, suggests that much of the decrease occurs in the lower stratosphere. . . . (see figure 8).*

The NSF, in cooperation with NASA and NOAA, organized a study of this phenomenon from August through October 1986.

A number of explanations have been suggested for the ozone phenomenon. One possibility is that it might result from chemical processes in the atmosphere, particularly the increase in chlorine in the stratosphere due to increasing emissions of chlorofluorocarbons. The stratospheric clouds that exist during the very low temperatures of the antarctic winter might be related; other theories suggest chemical reactions that depend on sunlight. Clearly changes in temperature and circulation contribute significantly to or are associated with changes

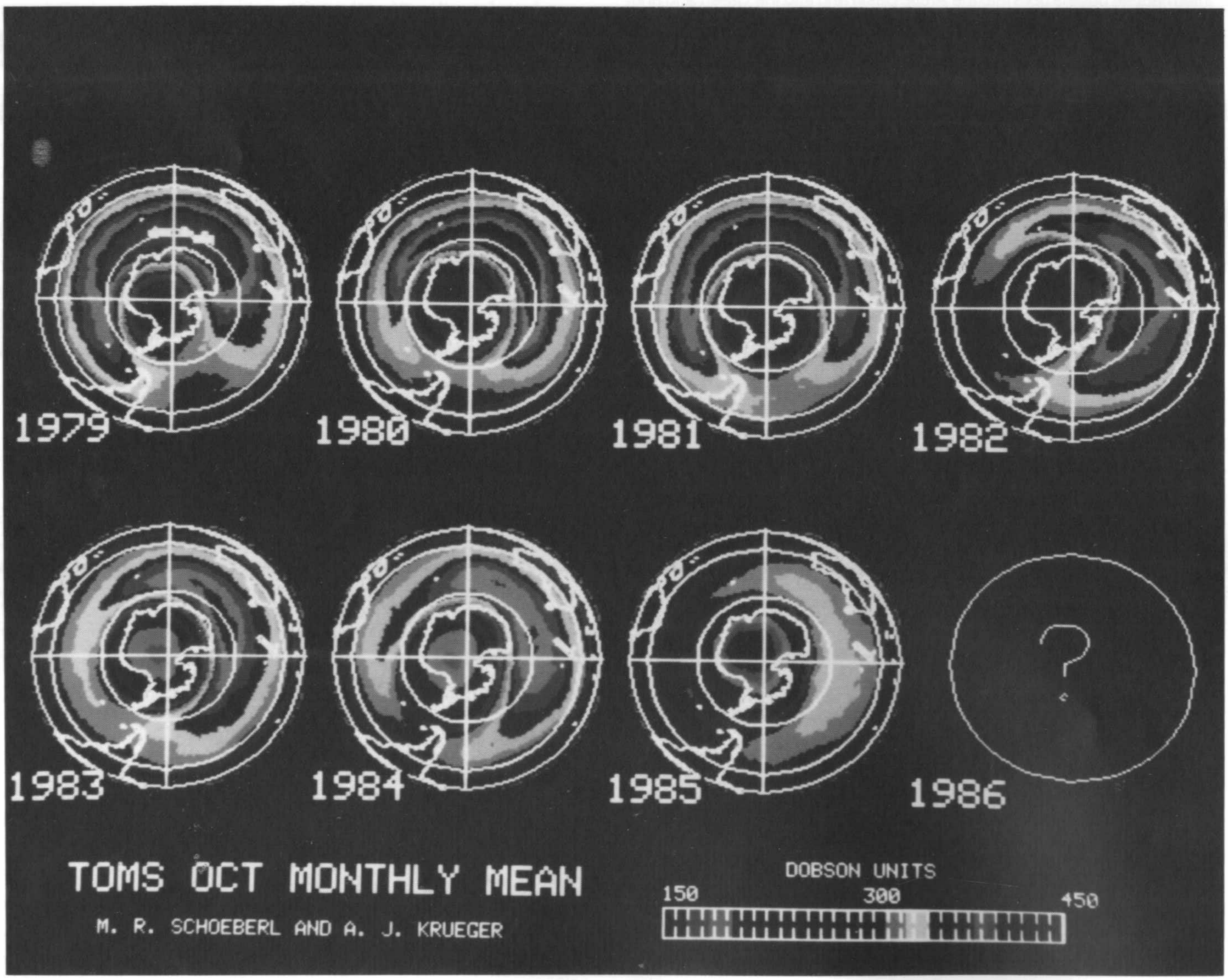

Figure 8. Total ozone mapping spectrometer (TOMS) aboard the Nimbus-7 satellite recorded these images of October ozone levels over Antarctica from 1979 to 1985.

in ozone, but there may be residual changes that need a chemical explanation. It is certain that the chemistry cannot be isolated from the dynamics. "The mechanism behind the ozone hole is still unknown." (Scholberl and Kruger, *Geophysical Research Letters*, 13, 1986, p. 1192).

Data on increases in average temperature at the sea surface show a strong negative correlation with the decrease in ozone. Because sea-surface temperature is closely related to the state of the atmosphere, it could be a factor in the ozone phenomenon. The unique properties of stratospheric-tropospheric exchange that characterize the atmosphere over Antarctica could also be related, as could cycles in solar activity and variability. Preliminary measurements taken at McMurdo Station between August and October 1986 showed that column abundances of nitrous oxide in the ozone hole were very low. This finding may be consistent with the chemical theory. The results so far suggest that effects of human activity, such as release of manmade chlorofluorocarbons, could be a factor in the seasonal decrease in ozone. Studies of the phenomenon will continue in 1987.

One effect of a decrease in stratospheric ozone would be an increase in the amount of ultraviolet radiation received by the earth. Results ranging from increased incidence of skin cancer to adverse changes in the productivity of Southern Ocean ecosystems might follow.

Because meteorology, atmospheric chemistry, and climate are multidisciplinary fields, NSF support is widely distributed among the discipline-based divisions. The DPP meteorology program focuses on participation in such research efforts as those dealing with arctic haze and the study of past climatic and atmospheric conditions through ice coring. The program in antarctic meteorology centers on global climate, mesoscale systems, and atmospheric chemistry. The new Global Change initiative in the NSF Directorate for Geosciences calls for study of the earth as a system of interacting physical, chemical, biological, and geological processes and offers an integrated, cooperative approach to understanding what is happening to global climate and what lies ahead. A closely related international effort is the World Climate Research Program. Research on the role of polar sea ice and ice sheets in climate is a key component of the First Implementation Plan for this program.

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OCEAN SCIENCES

The Arctic Ocean (figure 9) is often described as the least known area of the world ocean. About 60 percent of it is perennially covered with ice. The ice cover affects both the atmosphere above and the ocean beneath and can fluctuate widely; for example, the ice cover of the Greenland Sea varied by as much as 50 percent over a 30-year interval.

One of the main questions in ocean sciences is how the ocean is ventilated—that is, how are materials at the surface transported to the interior. This process affects climate, transfer of trace constituents and pollutants, and the carbon cycle. Ventilation results largely from the sinking of dense water at high-latitude locations, such as the seas between Greenland and Europe in the Arctic and the Weddell Sea in the Antarctic. Before 1979, the contributions of the Arctic Ocean to ventilation were not recognized because of lack of data. The Outer Continental Shelf Environmental Assessment Program in Alaska first indicated the production of dense water in certain shelf areas. Research east of Greenland showed dense water leaving the Arctic Ocean, mixing and ventilating the Norwegian Sea before it entered the North Atlantic and world ocean. Subsequently, data from two Canadian stations near the North Pole showed that deep ventilation occurs in the Arctic Ocean itself. These few stations in the Arctic Ocean (compared to many thousands of such stations in the rest of the world ocean), together with seemingly unrelated work on the periphery of the Arctic, showed that the Arctic Ocean and its adjacent seas, influence the deep waters of the world ocean (see figure 7 on page 17).

A long-term commitment to modern oceanographic measurements in the Arctic Ocean and adjacent seas is urgently needed. Recognizing this need and the potential progress in marine science that could result from such research, the Arctic Research Commission recom-

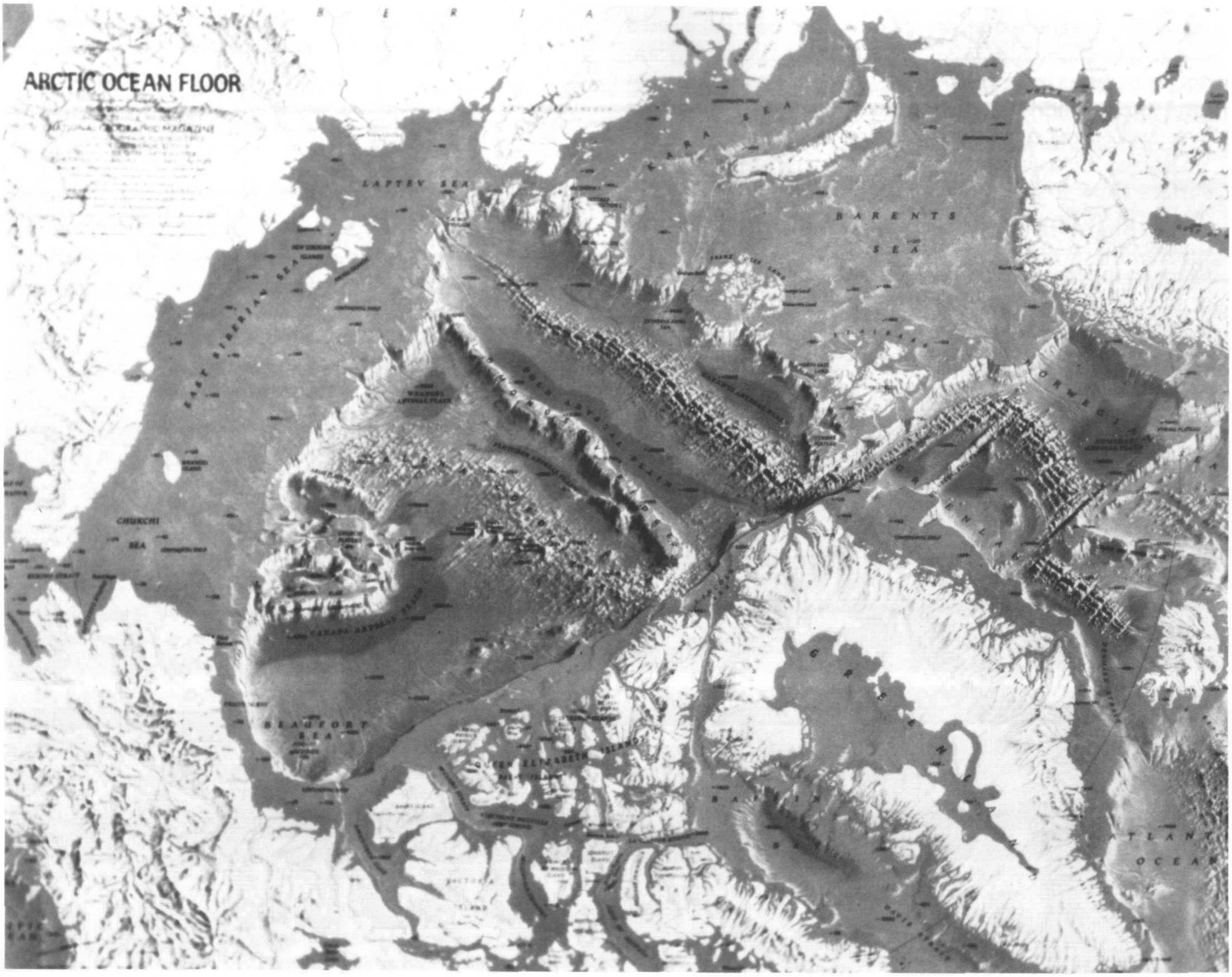

Figure 9. The Arctic Ocean floor.

mended, as its highest priority, study of the Arctic Ocean (including the Bering and marginal seas, sea ice, and seabed), and of how the ocean and the arctic atmosphere operate as coupled components (*National Needs and Arctic Research: A Framework for Action*, 1986).

The Polar Research Board also advocated a systematic program of oceanographic measurements to determine the large-scale circulation of the Arctic Ocean, its variability, and its dynamics. The Board recommended studies of convective renewal and mixing, mixing in the low-energy interior of the Arctic Ocean, effects of sea ice on ocean circulation and mixing, effects of cyclic formation and melting of ice on water properties, and effects of riverine inputs of fresh water and particulates (*National Issues and Research Priorities in the Arctic*, 1985).

Three major ocean science projects in the Arctic are the Marginal Ice Zone Experiment (MIZEX), the proposed Greenland Sea Project, and the Programme for International Polar Oceans Research (PIPOR). All are international projects. Each year the edge of the arctic ice field moves hundreds of kilometers north and south. The Office of Naval Research recognized that the processes associated with the location and behavior of the ice not only were fundamentally important to meteorologists, oceanographers, and biologists but also had implications for ocean transport, naval operations, management of living resources, and offshore minerals development. Therefore, it took the lead in organizing an international environmental research program. Objectives are to understand how air, sea, and ice processes in the marginal ice zone operate as a coupled system, as well as to understand the individual processes and their interrelationships. Three large-scale field investigations took place—MIZEX West in the Bering Sea (February 1983) and MIZEX East in the Greenland Sea (summer 1983 and 1984). These are the periods of greatest ice retreat. Field programs in 1987 and 1989 will focus on winter characteristics of the marginal ice zone. Ten countries are participating in the program (figure 10).

The Greenland Sea Project, guided by an international scientific committee, has the goal of understanding the large-scale, long-term interactions of air, sea, and ice in the Greenland Sea, including:

Figure 10. The Federal Republic of Germany's *Polarstern*, which participated in the MIZEX field investigations. (Source: U.S. Coast Guard.)

- the relationship of interannual variations in sea ice to climate
- the processes by which water types are produced and modified during ventilation
- the rates and means by which water masses and sea ice are transferred through circulation and mixing
- the atmospheric exchanges that drive the system
- biological processes—nutrient supply, organic carbon flux, microbial activities, and vertical transport.

The program is scheduled for 1987 through 1992 with follow-on monitoring through 2000.

The PIPOR, a joint European Space Agency/NASA program to study sea-ice dynamics in the Arctic Ocean and its marginal seas, will use a series of satellites, some of which have synthetic aperture radars. The first satellite in the project is the European ERS-1, scheduled for launch in 1990. To obtain nearly complete coverage of the Arctic, the European Space Agency and NASA are establishing satellite ground stations in Sweden, Alaska, and Canada.

Present emphases in the DPP arctic ocean sciences program include the Arctic Ocean Ventilation Project, the Acoustic Tomography Project in the Norwegian and Greenland Seas, and improved air/sea/ice models. These three activities bear directly on the objectives of the Greenland Sea Project. Future emphasis will be on increased use of remote sensing for sea-ice research, as well as on the extension of satellite-based ocean bathymetry reconstructions to high latitudes. Individual projects dealing with paleoenvironmental studies, geochemical relationships, and climate dynamics will continue.

These programs are consistent with priorities in both the *U.S. Arctic Research Plan* and the Polar Research Board report, *National Issues and Research Priorities in the Arctic*. The Plan emphasizes the need for testing and validating models of the interaction among ocean, ice, and atmosphere, long-term observational programs to improve data input to numerical models, and studies of ocean and sea-ice regimes on Alaskan continental shelves. These programs will advance basic knowledge, improve understanding of ecosystems on the shelves, and improve the cost effectiveness of offshore petroleum exploration and production.

The Southern Ocean (figure 11) includes about 10 percent of the world ocean and plays a major part in ocean mixing and global circulation. Its role in ventilating the ocean and supplying oceanic heat and moisture to the atmosphere makes it a major component of the global climate system. The Southern Ocean imposes a strong thermohaline signature of cold, low-salinity water on the world ocean, water that accounts for 54 percent of the total volume of the ocean. In thermohaline circulation processes, the sinking, northward motion of antarctic bottom water is compensated by the return flow of circumpolar deep water. The exchange of heat and fresh water between the ocean and the atmosphere drives southern ocean circulation; sea-ice cover modifies it. Variability of ice cover seems to be related to ocean-atmosphere exchange rates and water mass conversion.

The Antarctic Circumpolar Current (ACC), the only global-scale current, has a major role in the interocean exchange of water properties. Its transport is twice that of the Gulf Stream at its separation from Cape Hatteras. The eddy energy of the ACC varies with longitude and the nature of bottom topography.

The Southern Ocean is the focus of interdisciplinary research because of its relationship to the stability of global ocean circulation and climate, its uptake of substances from the atmosphere, its interaction with the antarctic ice sheets, and its effects on the distribution and variability of biota. It offers many research opportunities to solve key scientific questions. For example:

- What are the basic dynamics of the ACC, and how does it interact with subtropical and subpolar gyres?
- What are the eddy transports of heat, water, and buoyancy across the ACC?
- What are the energy, fresh water, momentum, and vorticity budgets of the Southern Ocean?
- What are the transfer processes between the Southern Ocean and the rest of the world ocean north of the ACC, and what is the total heat loss and gain of fresh water south of the ACC?
- How are local and large-scale interactions among ocean, ice, and atmosphere related to the distribution of sea ice?

- What are the ventilation rates and dominant processes responsible for these rates within the deep ocean and at the continental margins?

Although research on the Southern Ocean has advanced for the most part beyond surveys and basic data collection, observations during winter and in ice-covered regions are still needed and should receive attention in research planning.

Many of these questions are brought together in the World Ocean Circulation Experiment, an international research effort to construct, improve, and verify large-scale ocean models. Aspects to which the United States could contribute are field work on thermohaline tracer chemistry, data collection monitoring by satellites, drifters and moored sensor arrays, and theoretical research.

The Polar Research Board (*Research Emphases in the U.S. Antarctic Program*, 1983) recommended a high priority for research on ACC dynamics, the Weddell gyre (the largest of the subpolar gyres that transfer water mass properties), continental margins, and the sea-ice zone and emphasized the need for austral winter research. The DPP antarctic program in ocean sciences is based on these priorities and on the objectives of the World Ocean Circulation Experiment and the Global Ocean Flux study. Ocean sciences also will have a major part in the new Global Change initiative. If an icebreaking research vessel is available,* future DPP programs would include:

- the Ross Sea Heat Flux Experiment (to determine the effect of oceanic heat flux on basal melting and the stability of floating ice shelves)
- the Weddell Winter Experiment (to determine the structure, dynamics, sea-ice cover, and biota of the Weddell gyre during austral winter)
- the Aerogeophysics Project (a survey of geomagnetic and gravity anomalies in the Drake Passage and Weddell Sea to reconstruct the history of the Antarctic tectonic plate).

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*The NSF budget request contains an item for the lease and outfitting of an icebreaking research ship.

A new investigation scheduled to get under way within the next 2 years will deal with the formation and distribution of antarctic deep and intermediate water masses and the study of biogenic particulate cycling in the Ross Sea.

Detailed hydrographic and chemical observations from an icebreaking research vessel are an essential part of future field work and data collection in the Southern Ocean and the Arctic Ocean. As the Chairman of the Arctic Research Commission has stated in regard to research in the northern polar regions: "Serious and sustained marine research by U.S. scientists in polar seas . . . will not materialize unless a dedicated research vessel is made available." (Zumberge, J.H. Introduction to special issue on the Arctic Ocean, *Oceanus*, 29 (1), Spring 1986, p. 6)

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EARTH SCIENCES

Antarctica (figure 12) represents about 10 percent of the earth's continental area. Because geodynamic processes occurring within the continent and immediately adjacent areas have profoundly influenced the evolution of Earth's environment, Antarctica might be regarded as the global keystone to both the solid and fluid earth systems. The Antarctic Plate is one of the seven major lithospheric plates of earth and, unlike other plates, is nearly surrounded by a single type of plate boundary. The evolution of this plate is crucial to interpreting geodynamic history of the earth and offers special opportunities for the study of plate margin processes, including uplift, subsidence, and tectonic erosion of sediments from trench slopes.

The antarctic continent was once the hub of the now dispersed continents that made up the supercontinent of

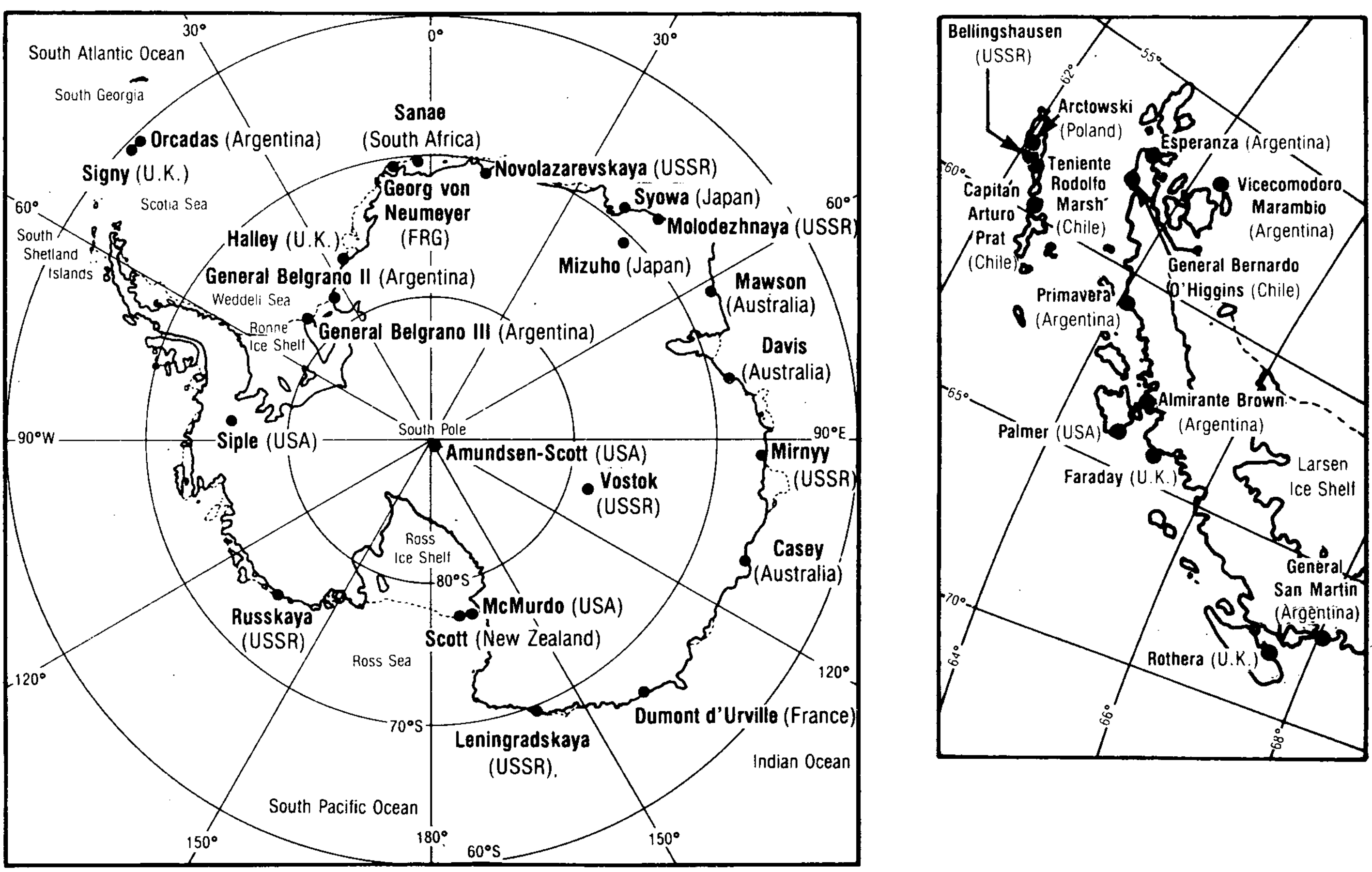
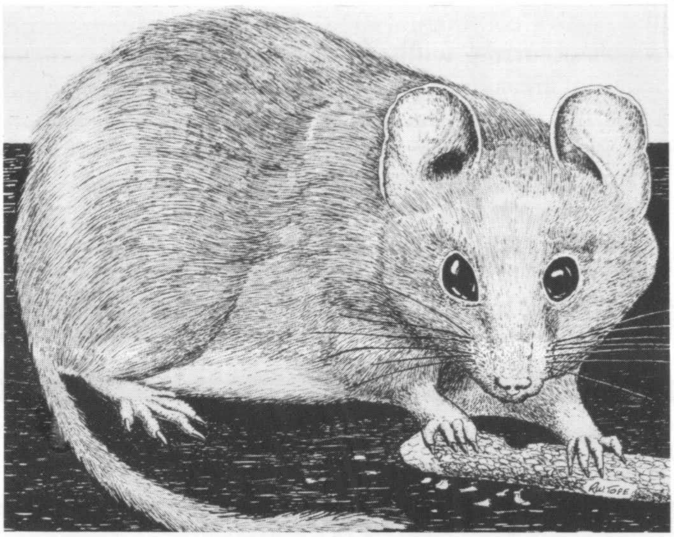


Figure 12. The antarctic continent.

Gondwana. The plate motions that dispersed the various continents began about 150-180 million years ago and continue today. The antarctic continent is unusual because it has remained in a near-polar position for more than 100 million years and because it is blanketed by a vast continental ice sheet with an average thickness of 3 kilometers. For a long period after arriving at its polar position, however, extensive continental ice sheets did not exist. Discoveries on Seymour Island of an early Tertiary marsupial (figure 13), on James Ross Island of a Cretaceous dinosaur, and near the Beardmore Glacier of fossils, wood, and pollen in tills containing marine microfossils of Pliocene age suggest that continental glaciation is a relatively recent phenomenon and that for much of the time since the breakup of Gondwana, Antarctica had a relatively mild climate.

The growth and development of the Antarctic Plate and of adjacent parts of the South American, African, Indian, and Pacific plates following the breakup of Gondwana included the formation of seaways and ocean basins. These seaways were critical in the development of oceanic circulation in the South Atlantic, the circumpolar



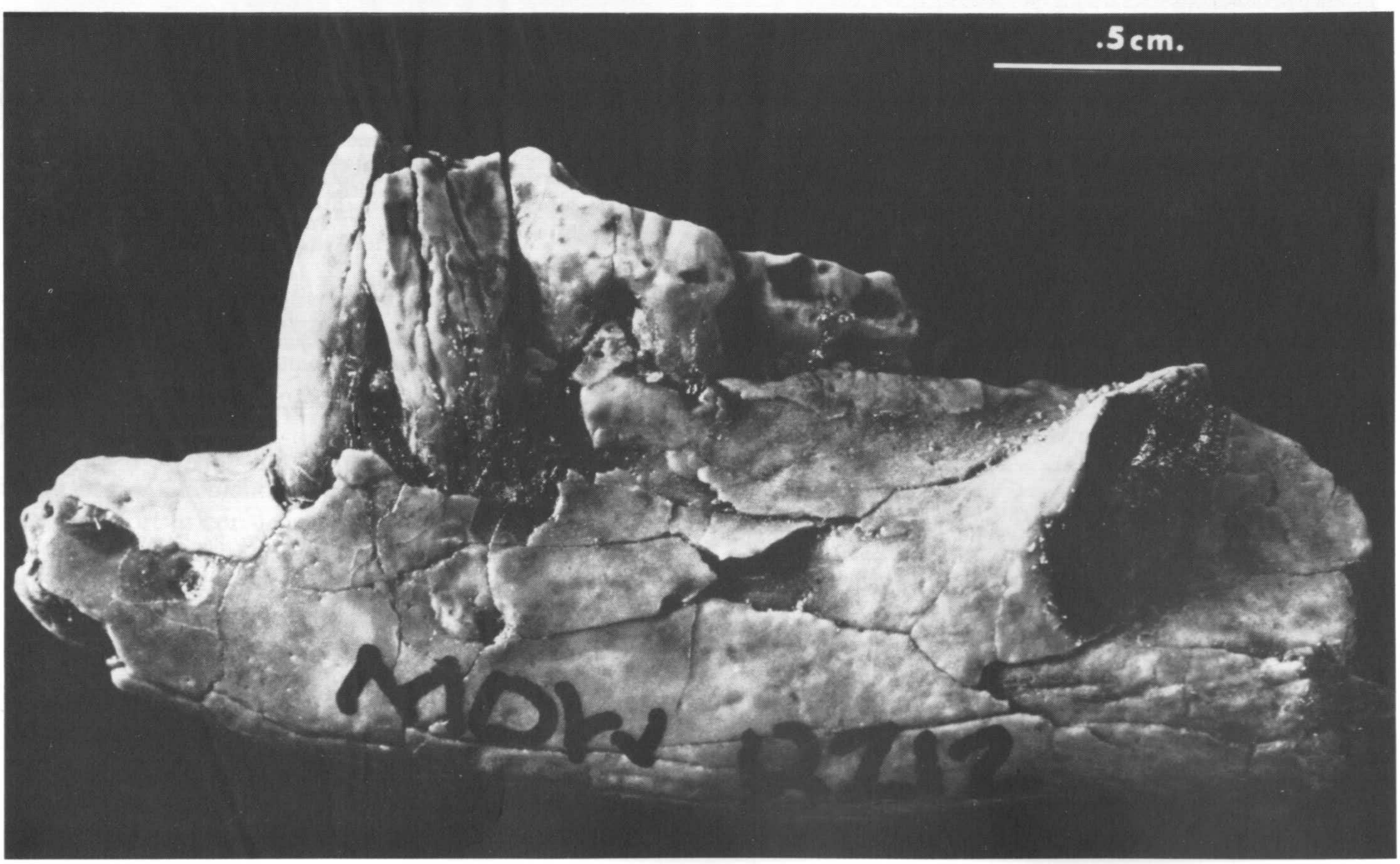


Figure 13. First fossil of an antarctic land mammal. The artist's conception (by R. W. Tope, Ohio State University) shows Polydolops, a fossil of which was found early in 1982 on Seymour Island, Antarctica. The animal was perhaps the size of a small wood rat and ate berries. Photo (courtesy of Ohio State University) is side view of a jaw fragment from the fossil. This remarkable find suggests that the land connection between the Antarctic Peninsula and South America 55 to 40 million years ago was even closer than scientists had thought.

circulation of the Southern Ocean, and the thermohaline circulation of the world ocean.

From a global perspective, highest priority research opportunities in antarctic geosciences, recommended in a recent Polar Research Board report *Antarctic Solid-Earth Sciences Research. A Guide for the Next Decade and Beyond*, 1986), are the following:

- determine the tectonic role of Antarctica in the breakup of the Gondwana supercontinent through plate tectonic processes, including investigation of the present seismically quiescent role of Antarctica within the dynamic earth
- determine the effect of the Gondwana breakup on the paleocirculation of the world oceans and on global paleoclimates, as well as present climate, and a better understanding of its biotic history
- reconstruct a more detailed history of the antarctic ice sheets and the definition of the physical, geological, and biological responses to them on both global and regional scales

From a regional perspective, it is important to understand the origin of the different crustal structure of East and West Antarctica and the transcontinental boundary—the Transantarctic Mountains—between them. East Antarctica appears to be a single, relatively stable crustal block; West Antarctica is composed of several "microplates" resulting from the breakup of Gondwana. The Transantarctic Mountains form a division between the 40-kilometer-thick crust of East Antarctica and the transitional 20 to 30-kilometer-thick crust of West Antarctica. The mountain boundary appears to be an interplate structure, but its nature, cause, time of formation, and potential of future motion are unknown.

Research in Antarctica also contributes to efforts to describe the breakup of Gondwana. Elements of the Gondwana Plate margin occur as scattered metamorphic and igneous rocks in West Antarctica and the Antarctic Peninsula. Vertebrate fossils of reptiles, amphibians, and mammal-like reptiles found in Antarctica suggest links with Australia and southern Africa. The more recent discoveries of dinosaurs and marsupials indicate an apparent closer relationship to South American species. All contribute to knowledge of Gondwana vertebrate paleontology and of the evolution and dispersion of vertebrate life.

The polar position that Antarctica has occupied for 100 million years presents unique opportunities for research. Some geologic phenomena could be the result of its polar position; others might best be studied because of it. For example, because of its polar position the antarctic continental shelves are the only places where glacial marine sedimentation, especially that associated with ice shelves, can be studied. The findings provide data for models to advance understanding of glacial sequences.

A high priority recommendation by the Polar Research Board (*U.S. Research in Antarctica in 2000 A.D. and Beyond*, 1986) was an integrated research program in marine geology and geophysics, oceanography, and marine biology on the continental shelves of Antarctica to characterize this environment. Such a program would advance understanding of:

- the evolution of the continental margin
- the mechanisms and temporal variations among the interrelated processes of sedimentation, sea-level change, glacial fluctuation, and lithospheric loading
- dynamic processes in the lower lithosphere and upper asthenosphere in a polar setting for comparison with studies in low-latitude regions
- offshore mineral and hydrocarbon potential

As such studies proceed to the deeper margin, deep, high-resolution seismic imaging together with deep drilling and sampling will be required. Instrumented, subseabed boreholes can serve as "laboratories" for long-term studies and monitoring. Among the requirements for productive marine geology and geophysics are multichannel seismic equipment on ships capable of surveying in sea ice and a deep-sea drilling vessel that can operate in a moderate sea-ice environment. Airborne geophysical survey capabilities and satellite observations would also be necessary.

Among the top priorities recommended for research on the antarctic continent (*Antarctic Solid-Earth Sciences Research . . .*, 1986) are the following:

- determine the crustal structure of Antarctica, including the geologic history and structural relationships between the crustal blocks of West and East Antarctica
- study the evolution of sedimentary basins, both within greater Gondwana before breakup and within the antarctic continent subsequent to breakup. (Because of the ice cover, most of the continent's 3-billion-year geological record is inaccessible; therefore, research will require "remote sampling" or drilling a relatively deep hole to sample the otherwise inaccessible stratigraphic record.) (figure 14)

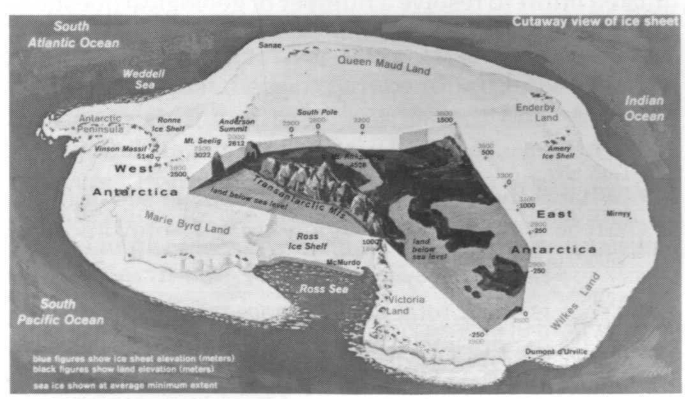


Figure 14. Cutaway view of the antarctic ice sheet. (Source: *Polar Region Atlas*. National Foreign Assessment Center, CIA, Washington, D.C., 1978.)

- study the uplift of the Transantarctic Mountains (this orogeny is important because of its relationship to discontinuities in the antarctic crust, development of basins, and formation and fluctuations of the ice sheets)

- study the role of Antarctica in the evolution of the earth's biosphere, including the history of the biotic bridges between the southern continents, high-latitude evolutionary processes, and their impact on mid- and low-latitude paleobiology.

A number of geologic phenomena are unique to Antarctica but are not related to its polar position or to global processes. For example, Mt. Erebus on Ross Island presents some unique opportunities for the study of volcanic processes, and the silicified peat deposits in the Transantarctic Mountains provide a rare opportunity for study of plant anatomy and histology, fungal growth, and spore formation. Such studies, comparable to those conducted on living plants, can be very informative, especially when the fossil record is not limited to plant impressions and compressions.

The main thrusts of DPP earth sciences research in Antarctica are (a) a coordinated program of geophysical studies to understand the relationship between the East and West Antarctic plates and the intervening Transantarctic Mountains and (b) determination of the geology and the geological and biological history of Antarctica. Such studies will include work on the continental margins, for only by combining the results of marine geological and geophysical studies with those on the continent will the entire tectonic picture of Antarctica become clear.

The Arctic Basin and surrounding continental areas (figure 15) comprise an actively spreading ocean basin and geodynamic system that is the geological complement to the southern polar regions. At present, earth scientists have only the broadest picture of the structure and evolution of the Arctic Basin and its relationship to the continental plates that surround it. To advance knowledge of the circumarctic regions will require a coordinated effort to resolve a number of geological questions of regional and global scope:

- When did the "modern" configuration of the Arctic Basin and the surrounding continents form, and what was the history of its tectonic evolution?

- What is the basic geology of the Soviet sector of the Arctic, especially the region of the Laptev and East Siberian Seas?

- What is the Cretaceous paleoceanic history of the arctic region, including possible episodes of widespread anoxia? (In this context, the Arctic constitutes 7 percent of the world's area, yet it contains about 10 percent of world petroleum reserves and some 30 percent of world gas reserves.)

- What is the paleoclimatic history of the Arctic, especially the detailed history of Cenozoic climatic variations?

- What are the sedimentary processes peculiar to high-latitude regions?

- What is the arctic paleotemperature history of the last few 100 years? (Recent research on permafrost indicates that the history of local surface temperature can be reconstructed in detail.)

- What are the processes and rates of geomorphic change in an arctic terrain? (Surficial processes and stability are fundamental to an understanding of the arctic environment and its impact on human activities in the Arctic.)

Emphasis in the NSF earth sciences program in the Arctic is on paleoclimatic and paleoecological reconstructions and on the structure and origin of the Arctic Basin. Some of this research is conducted in Greenland and Spitzbergen.

Earth sciences research in the polar regions is evolving rapidly. New geophysical and geochemical methods and improved sampling techniques are being used to discover, describe, and quantify a wide range of phenomena and processes. New data, methods, and ideas and improved logistic capability to support research in the polar environment will accelerate the resurgence of all compo-

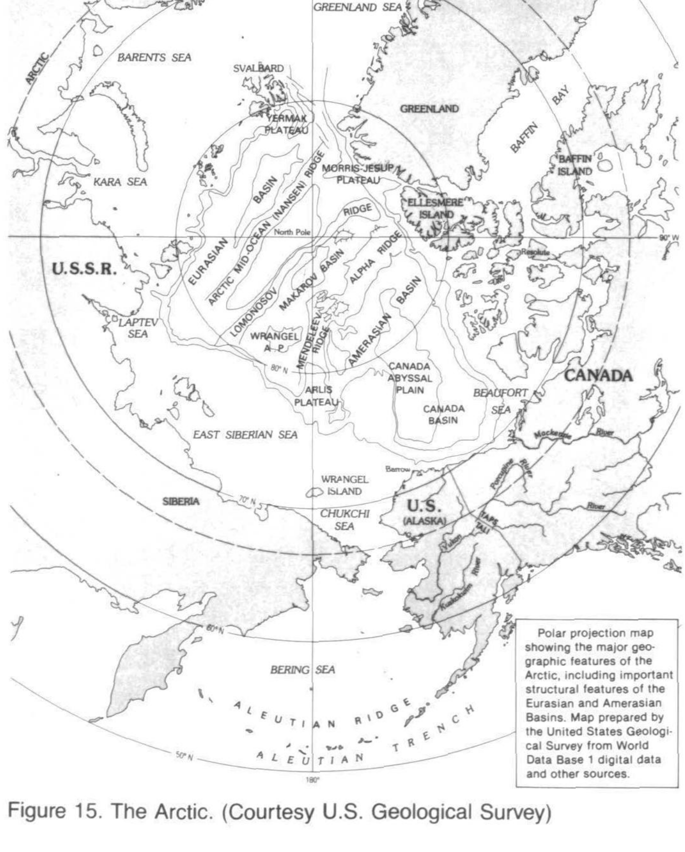


Figure 15. The Arctic. (Courtesy U.S. Geological Survey)

nents of polar sciences. Both a need and a basis exist for integration of the polar regions into the global perspective of earth history and into models of natural processes on global and regional scales.

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GLACIOLOGY

Glaciology, including the science of all major forms of naturally occurring ice (floating ice, glaciers and ice sheets, seasonal ice, and ice in the ground) is particularly appropriate for polar research programs. It is an especially exciting field, offering many scientific opportunities, and is closely related to environmental issues of increasing concern. Ice is central to the physical processes that determine climate and provides a unique record of environmental history, showing how climate has changed in the past. Further, warming of oceans and atmosphere brought about by the buildup of so-called "greenhouse gases" would be accentuated in polar regions, could lead to significant changes in sea level, and have other impacts on global environment. Glaciology will be a major component of the international, interdisciplinary effort to understand and predict global environmental change.

Opportunities for research with application to contemporary problems include extraction of climatic and environmental history from ice cores, glacier and ice sheet dynamics, sea ice dynamics, seasonal snow cover, and permafrost. Cores from the Antarctic and Greenland Ice Sheets provide a unique opportunity to sample ancient atmospheres with a time resolution ranging from 1 year to several centuries for the deepest cores. Such cores reveal the buildup of atmospheric carbon dioxide, oxygen isotopes, methane, lead compounds, chlorofluorocarbons, trace gases, and particulates since the Industrial Revolution. A recent core from Greenland shows abrupt fluctuations in air temperature, atmospheric dust, and carbon dioxide occurring in just a few decades. A core from Antarctica obtained by Soviet scientists has extended the record of climatic history back through the last interglacial about 150,000 years ago. Ice caps at high altitude in lower latitudes also contribute to the global climate picture. For example, cores from the Quelccaya Ice Cap in Peru show 1,500 years of precipitation, air temperature, and atmospheric fallout, providing a history of El Nino occurrences. Such results have advanced understanding, but many questions remain:

- To what extent are the apparent high-frequency climatic fluctuations seen in high-resolution ice cores from polar regions correlated with data from cores taken at lower-latitude locations?
- What is the geographic extent of climatic events shown in ice cores?
- How can deep ice cores be more precisely dated, especially in ways that are independent of ocean-sediment core histories?
- What are the geographic extent, history, and synchroneity of events that led to the Little Ice Age* and its amelioration?
- What can the record of atmospheric chemistry in air trapped in ice reveal about the process of biogeochemical cycling?
- Did the West Antarctic Ice Sheet disintegrate during the last interglacial?
- Can the ice core record be extended back to 500,000 or more years ago to provide information on the astronomical forcing of climatic change?

An expanded program of ice-core drilling is a top priority in both polar regions, as reflected in Polar Research Board reports (*Snow and Ice Research. An Assessment*, 1983, and *Recommendations for a U.S. Ice Coring Program*, 1986) and NSF program planning. The Board recommended that the NSF "should be the lead agency in funding a new Ice Coring and Analysis Program (ICAP), and should manage the program on behalf of the scientific community." (*Recommendations for a U.S. Ice Coring Program*, 1986, p. 7) A 10-year program is suggested, with the objectives of obtaining high-resolution climatic time series, with wide geographic coverage, over the past several thousand years by analyses of cores from various depths at many locations in polar and nonpolar regions, and obtaining long-period climatic time series of several hundred thousand years from both polar regions. The Board further calls attention to the need to update U.S. laboratory facilities to increase the efficiency of ice sample analysis. In regard to drilling capability, it recommends:

- maintaining and updating the present shallow and intermediate depth core drill inventory

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*A period of cold climate and advances of mountain glaciers beginning in the 12th and 13th centuries and lasting in some areas until about 1950.

- acquiring an intermediate core drill that can operate in a fluid filled hole to improve core quality and extend the accessible depth coverage
- building a deep drill based on the most current technology.

The proposed ICAP endeavor would include short, intermediate and deep drilling, careful site selection, multiple cores in some areas, and a plan of cooperation among many institutions in all phases of the program. The Greenland Ice Sheet Program, a cooperative effort of the United States, Denmark, and Switzerland, was a highly successful ice-coring research effort. Currently in the planning stage is a second international collaborative deep drilling program in Greenland to take place over the next 5 years or so. DPP's future plans also include continuation of shallow and intermediate drilling. The DPP has noted the need to develop a U.S. deep-drilling capability that will permit drilling to bedrock through cold ice to 3,000 meters, with retrieval of high-quality cores. Additionally, DPP is considering a hot-water drilling system that would penetrate over 1,000 meters, provide access to the interface between ice and bedrock, and permit drilling to various depths within ice sheets and glaciers.

Other studies in polar regions (e.g., figures 16 and 17) can augment knowledge of past climate, environmental change, and evolution of glaciers and ice sheets. Such

GREENLAND ICE THICKNESS SECTION

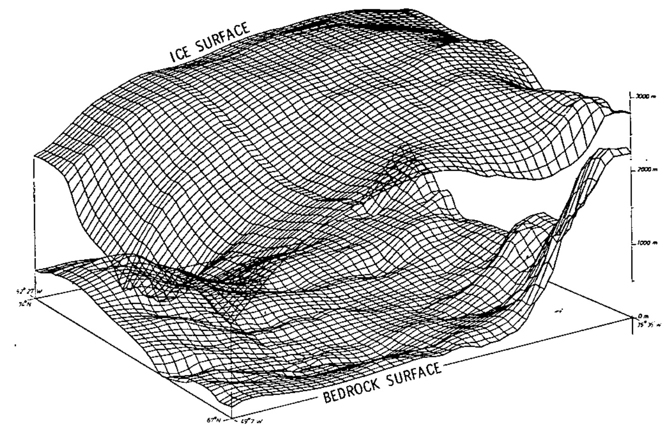

Figure 16. This computer-generated cross section of a central portion of the Greenland Ice Sheet was based on radio echo sounding data collected by USARP LC-130 airplanes. The diagram shows the ice surface and bedrock. Such ice thickness data, combined with ice flow studies and other measurements will enable Greenland Ice Sheet Project investigators to determine the history of an ice core drilled from the surface to bedrock at a single point on the ice sheet.

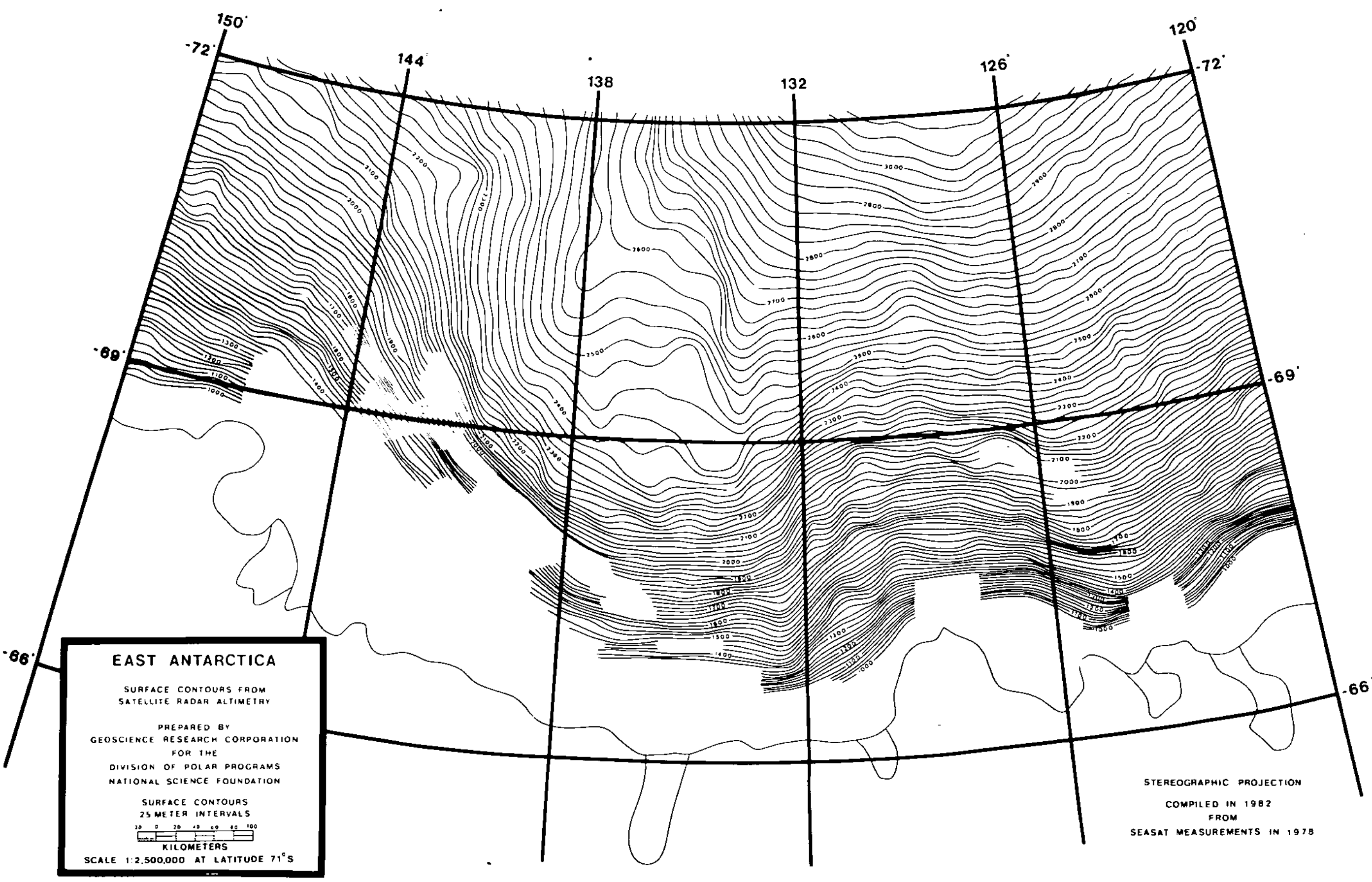

Figure 17. This 25-meter, ice-sheet contour map was derived from altimeter measurements made by the satellite Seasat. To prepare the map, scientists divided a 650,000-square-kilometer area, located between 120°E and 150°E and from the coast to 74°S into rectangles with sides of 0.25° latitude (27.8 kilometers) by 0.25° longitude (8.6 to 10.8 kilometers, depending upon the latitude). On this map the area bounded by 126°E and 138°E and 69°S and 72°S is the extension of ice from Dome C (75°S 125°E), one of the three highest areas on the East Antarctic ice plateau.

studies include research on fluctuations of glacial and sea-ice margins, changes in the rate and types of sediment deposited on continental shelves by glacial runoff, biological evidence (pollen, insects, ostracods) in lakes, bogs, soil, and ocean sediments, and temperature profiles in perennially frozen ground (permafrost). A program of coring sediments below frozen lakes could yield environmental information from a wide range of geographic sites.

Another high priority in glaciology in both polar regions is glacier and ice-sheet dynamics (figure 18). The *U.S. Arctic Research Plan* emphasizes such research and describes needed studies. Polar Research Board reports (for example, *Snow and Ice Research. An Assessment*, 1983) also give this research high priority. Of particular interest to both glaciologists and climatologists are the following problems:

- possible disintegration of the West Antarctic Ice Sheet, with a consequent rise in global sea level
- prediction of iceberg calving in tidewater glaciers
- understanding of glacial surges or why certain glaciers periodically accelerate their flow, advance rapidly, then become quiescent again

The flow from the Antarctic and Greenland Ice Sheets forms ice streams that continue to the coast, then out to sea as floating ice shelves or glacier tongues. The process by which glacial sliding occurs is not well understood. Recent evidence of the presence of a water-saturated, 6-meter-thick layer of till on which an ice stream slides has resulted in a new perspective on ice dynamics and a set of new questions related to the formation of "till deltas" and upstream erosion.

Transfer of heat from oceans to the bottom of ice shelves, with resultant melting, is another aspect of the dynamics of ice sheets and streams that requires study and is basic to understanding the response of the West Antarctic Ice Sheet to climatic warming.

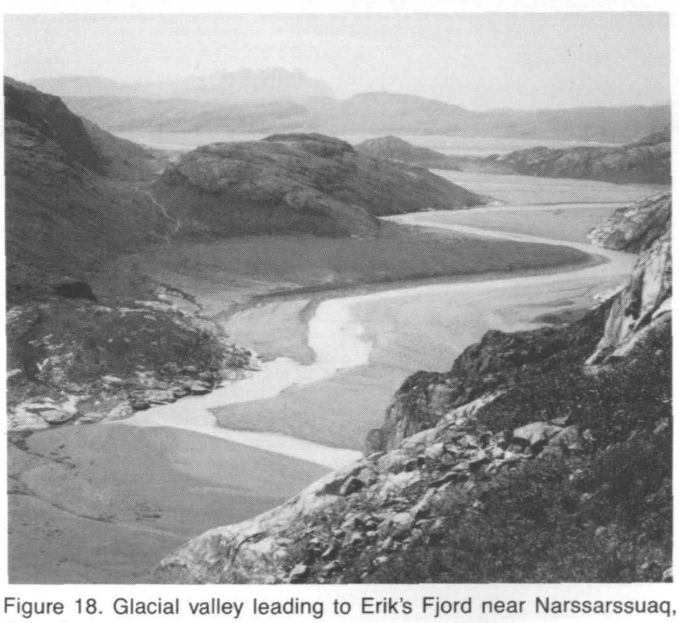

Figure 18. Glacial valley leading to Erik's Fjord near Narssarssuaq, Greenland.

Tidewater glaciers (figure 19) that calve to form icebergs pose a number of research questions related to their nonsteady states, calving instability, and often rapid sliding. The Jakobshavn Glacier drains about 11 percent of the Greenland Ice Sheet and produces many of the icebergs that drift into the North Atlantic sealanes and oil exploration fields off Labrador. The Columbia Glacier in Alaska has begun to disintegrate and will open a new 30-kilometer-long fjord over the next few decades. The Hubbard Glacier, also in Alaska, is advancing and in 1986 temporarily sealed off Russell Fjord. These events present opportunities to study fundamental processes of rapid sliding, the formation of ice streams, and the rate and stability of iceberg calving. DPP arctic program plans include continued research on the ice dynamics of Alaskan glaciers with emphasis on the processes leading to glacial surges (figure 20).

The relationship of sea-level rise to glacial melting is another question of current concern. A recent Polar Research Board report (*Glaciers, Ice Sheets, and Sea Level: Effects of a Co_2-Induced Climatic Change*, 1985) indicates that Alaskan glaciers probably contributed the greater part of the change in ocean volume (apart from expansion due to temperature effects) observed over the past century.

Sea ice plays a key role in climate and marine ecosystems (see also sections on Meteorology and Climate, Ocean Sciences, and Biology and Ecology). It is one of the most perishable constituents of the earth's surface. Freezing of sea water removes carbon dioxide from the atmosphere, but the process and rate of uptake are unclear. Sea ice is also directly related to the formation of deep water in oceans. Analyses of global water masses have shown that three-fourths of the water masses obtain their properties from 5 percent of the global ocean surface, all of which is located at high latitudes. New remote-sensing techniques offer opportunities for research on sea ice. Together with passive microwave data and drifting buoys, these new techniques should advance under-

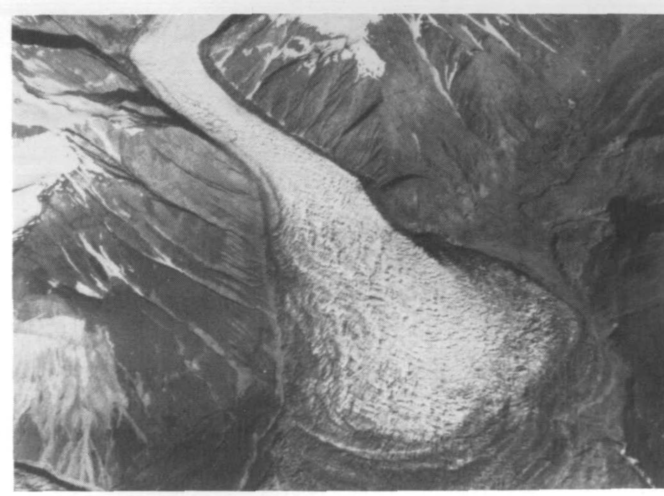

Figure 19. Variegated Glacier

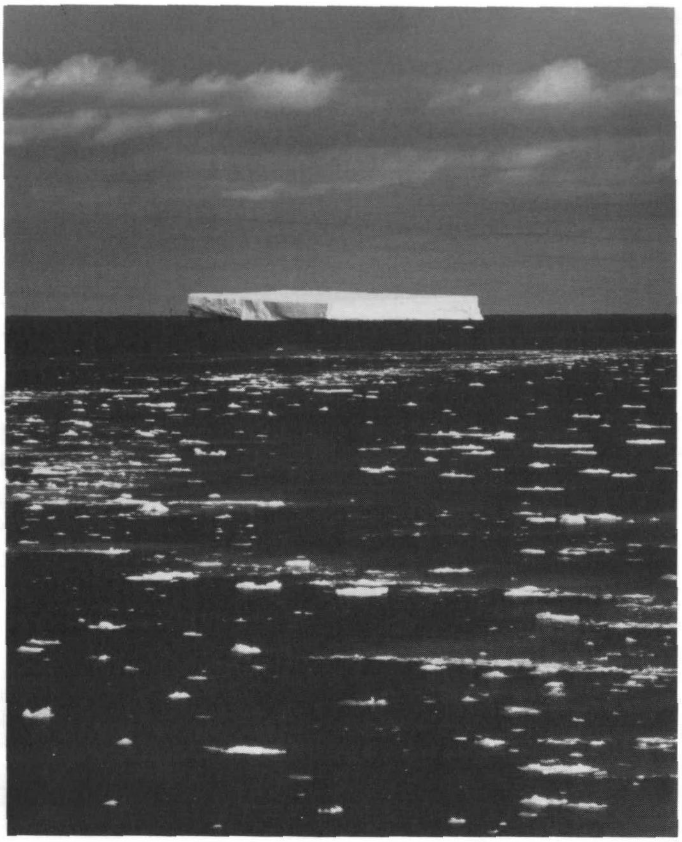

Figure 20. Tabular iceberg

standing of the mechanical and thermodynamic evolution of sea ice. Sea ice receives a high priority in research planning not only because of its scientific challenges and environmental impacts but because of the practical needs related to icing of structures (figure 21), ice forces on stationary structures and ship hulls, effects on military operations, and hazards to marine shipping and transportation.

Snow, the most reflective material on the earth's surface and the most variable, directly influences weather. The surface radiation balance affects the temperature and humidity of the overlying atmosphere, thus atmospheric circulation and weather patterns, which extend from the polar to the middle latitudes. In the Arctic and in areas at lower latitudes as well, the principal concern about snow relates to transportation and to such hazards as impacts of avalanches and floods. Climate studies require large-scale measurements of snow mass and areal extent to validate models and to provide forecasts of water resources. Satellite remote sensing offers the possibility of rapid data acquisition on the extent of snow, snow mass (water equivalent), and wetness (liquid water content). A multifrequency, passive microwave system would be required. The Polar Research Board (*National Issues and Research Priorities in the Arctic*, 1985) recommended development of remote-sensing methods for synoptic scale, all-weather determination of the extent and mass of snow cover, based on ground truth verification and improve-

Figure 21. Icing of structures, a hazard to drilling rigs and fishing vessels. (NSF photo by Russ Kinne.)

ments in theory. The *U.S. Arctic Research Plan* also calls for improved models to predict snowmelt and runoff.

Permafrost presents a variety of scientific questions and affects nearly every aspect of life in the Arctic. Almost all the land areas north of the Arctic Circle and much of the continental shelf of the Arctic Ocean are within the permafrost zone. Permafrost underlies three-fourths of Alaska. Summer thawing produces an "active layer" that can be as thick as 2 meters; the ground beneath remains below 0°C. A basic understanding of thermal and mechanical properties in permafrost is essential to arctic engineering and also to the study of geomorphic processes and the evaluation of the contemporary landscape.

Temperature measurements in widespread boreholes on the Alaskan Arctic Slope have shown that the surface temperature at most sites increased by 2° to 4°C over the past 100 years. This warming is occurring in the area where anthropogenic climatic change could be greatest and perhaps first observable. It is important to continue to monitor temperatures and rate of change in permafrost at present sites and additional ones and to determine (a) causes of the rapid increase in near-surface temperature, (b) how widespread the effect is, and (c) whether ecosystems reflect this change.

Priorities recommended by the Polar Research Board (*Permafrost Research: An Assessment of Future Needs*, 1983) include detection and mapping of permafrost and ground ice, studies of active layer and permafrost temperatures, improved methods to predict heat and mass transport in and across the boundaries of permafrost, studies of ice segregation and origins of ground ice, and studies of properties of permafrost (including physical and mechanical properties, stress/strain/time/temperature relationships, thermal stress and fracture, and characteristics of saline permafrost). The *U.S. Arctic Research Plan* calls for a comprehensive, long-term program of ground temperature measurements, preparation of maps of mean annual temperatures, and studies of the distribution and characteristics of permafrost and of disturbance and recovery of permafrost terrain.

NSF-supported research on permafrost includes determination of the occurrence, distribution, and origin of frozen soils and ground ice, development of methods to study subsea permafrost, and paleoclimate studies.

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UPPER-ATMOSPHERE RESEARCH AND ASTRONOMY

Between the sun and earth, electromagnetic radiation, gases, and dust that can only be measured remotely or by spacecraft fill space. As these interact with the earth's magnetic field, they affect the operation of telegraph and telephone systems, oceanic cables, radio, radar, and various surveillance and defense systems. Although the physics of the upper atmosphere and near-earth space might be considered an esoteric field, it is vital to national defense and communications and is a field for which the polar regions provide unique data. The objective of research on the upper atmosphere is to understand how the energy carried from the sun interacts with earth systems, and how it produces such phenomena as magnetic storms, ionospheric disturbances, and the aurora (lights in the upper atmosphere at an altitude between 90 and 300 kilometers) (figure 22). The processes linking the sun to the earth are highly complex. The earth's magnetic field extends out into intérplanetary space. The sun has a hot atmosphere of some several million degrees (the solar corona) that flows from the sun out through the solar system and is called the solar wind (figure 23). At

Figure 22. Aurora

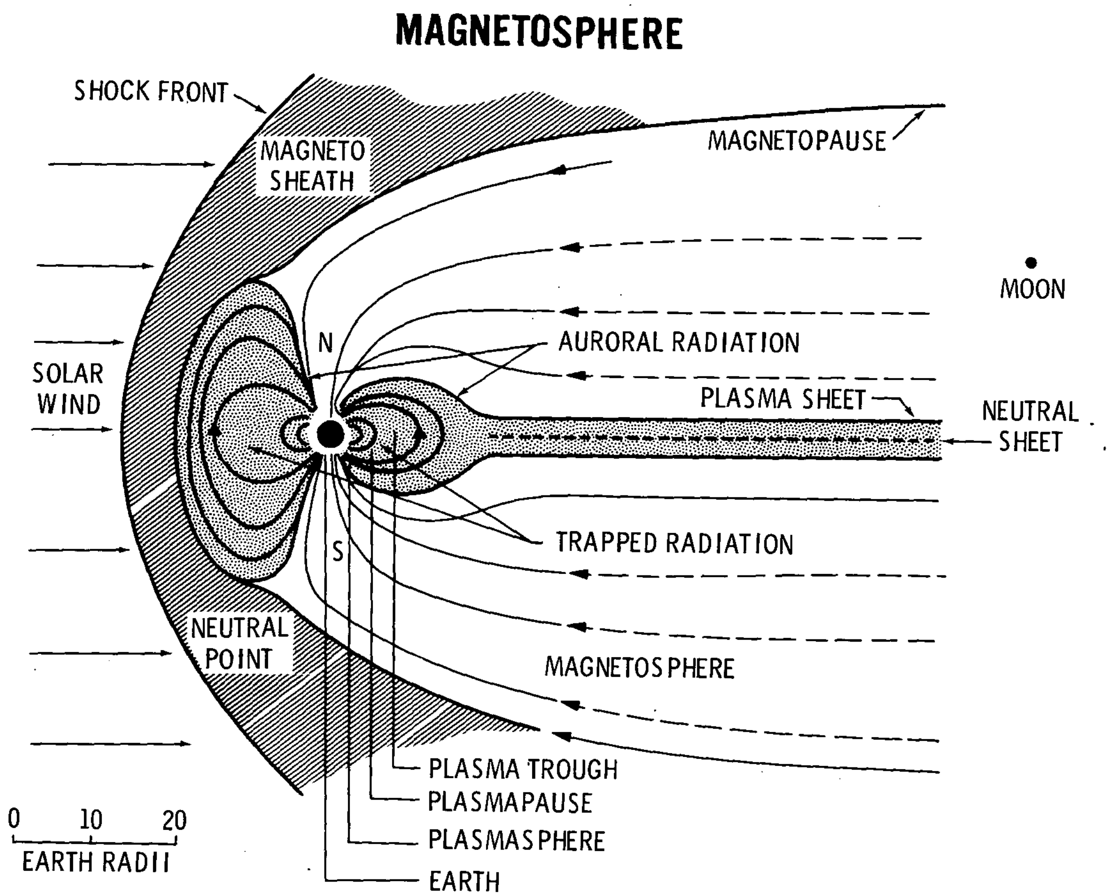

Figure 23. Sun-earth interaction via the solar wind.

the earth's orbit, this gas consists of low-density particles (primarily photons and electrons) with energy of about 1 kiloelectron volt and can cause disruption in power lines and communication systems. The solar wind is an electrically charged gas. Because of its high electrical conductivity, it carries the solar magnetic field as it expands into space. The interaction between the earth system and the solar wind occurs principally through the earth's magnetic field, which deflects the solar wind, creating a kind of cavity, called the magnetosphere, in the interplanetary medium. Some of the energy of the solar wind is trapped in the magnetosphere, while some is transmitted and deposited in the neutral atmosphere during magnetic substorms. A magnetic substorm causes brightening of the aurora and intensifies electric currents flowing in the ionosphere (the region of the atmosphere from about 90 to about 1,000 kilometers altitude).

The upper atmosphere in the polar regions has been called "earth's window to outer space," for many effects occurring there are manifestations of deep-space phenomena and may be observed from the ground. Such observations are possible because processes occurring in the outer portions of the magnetosphere often can be traced back to earth along magnetic field lines, which intercept the earth's surface in the polar regions. The so-called polar cusps are regions that separate the earth's magnetic field lines that close on the sunward boundary from those that stretch into the magnetosphere tail. Because in the polar cusp regions the shielding effect of the earth's magnetic field can vanish, solar wind plasma can penetrate directly into the magnetosphere and release charged particles into the ionosphere along the dayside auroral oval. Although some measurements have been made from spacecraft, little is known about the physics of the regions.

A number of magnetospheric effects can be studied through polar observations. These include the motions of atmospheric ions, electrons, neutral gas, optical and X-ray emissions, magnetic perturbations from flows of electrical currents, temperature changes, variations in spatial distributions of plasmas (ionized gases), plasma turbulence, and radio emissions. The most conspicuous polar manifestation of the magnetospheric activity is the aurora. The auroral zones are keys to understanding the dynamics of the whole upper atmosphere, an environment that can change on a scale from seconds to hours (figure 24).

Geomagnetic field lines from outer regions of the magnetosphere intercept the ionosphere and the surface of the earth in the polar regions and can be traced from one hemisphere to the other. Observing locations at opposite ends of a magnetic field line are called conjugate points. Several sites in Antarctica have conjugate points in the Northern Hemisphere (Canada, Greenland, and Iceland)

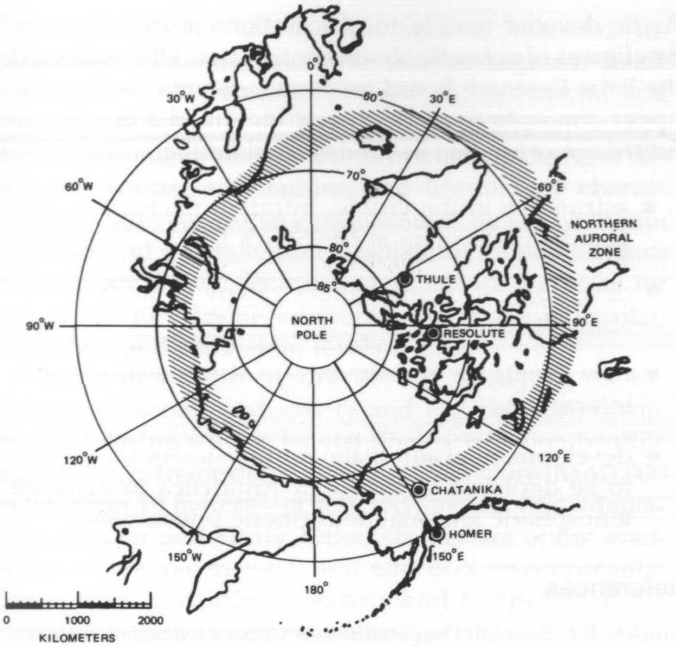

Figure 24. Location of the aurora over North America.

at which simultaneous measurements are made. Together with data from spacecraft, these data are providing new insights into the earth's ionosphere and outer magnetosphere.

Antarctica offers other unique advantages for upper atmosphere research, including low electromagnetic noise background, good atmospheric viewing conditions, an extensive thick ice sheet of nearly uniform dielectric properties, and the absence of national boundaries. Experiments that are suited to an antarctic location are very large antenna arrays on the ice sheet, studies concerned with north/south asymmetries or with global interrelationships, and optical cusp studies. South Pole station is uniquely suited for optical cusp studies because this site provides a particular conjunction of geographic and geomagnetic aspects. For example, the southern auroral oval experiences 24 hours of darkness in the austral winter, something which does not occur in the Arctic. Antarctica is also as a good location for sounding rocket and balloon studies.

Some of the principal research opportunities in upper atmosphere physics include the following:

- antarctic ground-based observing sites and rocket experiments to determine the dynamics of the aurora and the structure of the transpolar arc
- collection of magnetic field data in Antarctica to supplement observations from sites in the Northern Hemisphere and to provide a global index of the occurrence of magnetic substorms
- a meridional observatory array extending down the Antarctic Peninsula to provide simultaneous observations of auroral and magnetic disturbances and to monitor expansion of the aurora in response to magnetic substorms
- conjugate measurements in the Antarctic and the Arctic to understand the occurrence of magnetic perturbations in both hemispheres and disturbances in the magnetosphere, in order to improve understanding of the sources of these disturbances
- measurements of charged particle precipitation from the magnetosphere into the earth's atmosphere over antarctic sites. (Because the earth's magnetic field is weak in the South Atlantic compared to the northern hemisphere conjugate region, this area and the Antarctic Peninsula comprise a sink for trapped particles and can be used to map regions of magnetosphere wave-particle interaction.)
- injection of very-low-frequency (VLF) waves into the ionosphere and magnetosphere from ground-based transmitter facilities in the Antarctic (figure 25)
- simultaneous measurements of neutral winds and ion drifts along the auroral oval and in the polar cap to advance understanding of plasma transport over the polar caps
- high-altitude balloon measurements during the austral summer to provide data on the magnetosphere and to complement the ground-based observations
- electron tracer experiments using rockets launched from Antarctica to inject an electron beam into the magnetosphere so that characteristics of the electrons that traverse to the opposite hemisphere and return can be measured, yielding data on large-scale magnetospheric electrified fields

The Polar Research Board recommended (*Research Emphases for the U.S. Antarctic Program*, 1983) that high priority be given to two research questions in upper atmosphere physics that further emphasize some of the opportunities listed above:

- What are the spatial and temporal characteristics of particle precipitation, magnetic-field-aligned and

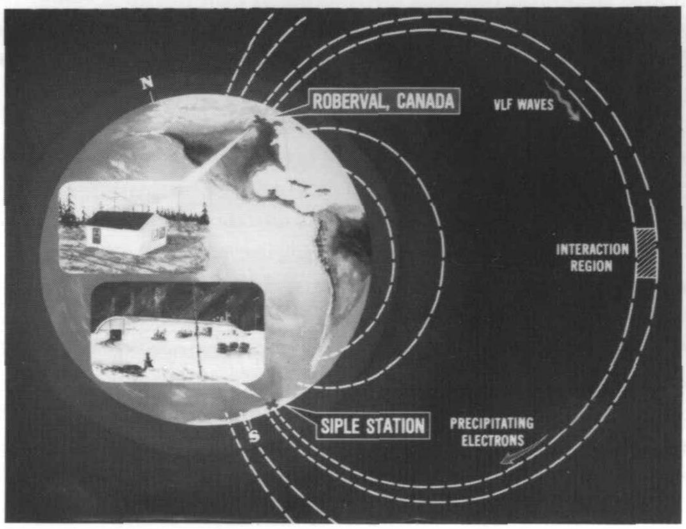

Figure 25. Whistler-mode wave-particle interactions.

ionospheric electric currents, and electromagnetic emissions at very high geomagnetic latitudes?

- What are the physical processes in the magnetospheric plasmas that govern energy flow and conversion along the entire magnetic field line between conjugate points in opposite hemispheres?

The Board also stressed the need to continue magnetic, riometer (an acronym for relative ionospheric opacity meter), and ionospheric measurements and optical observations of aurora at South Pole Station, as well as cosmic-ray studies at McMurdo and solar observations at South Pole.

In the North, the Arctic Research Commission recommended as its third highest priority "Research to understand the high-latitude upper atmosphere and its extension into the magnetosphere. Emphasis should be on advancing prediction of disturbances in space and mitigating their effects on high-latitude communication and defense systems (*National Needs and Arctic Research. A Framework for Action*", 1986). The Polar Research Board, in its assessment of research needs in the Arctic (*National Issues and Research Priorities in the Arctic*, 1985), also stressed the need for upper atmosphere research, listed a number of questions that should receive priority attention, and called for a comprehensive, long-term coordinated program of ground-based, rocket, and satellite observations.

The polar regions, particularly the Antarctic, also provide opportunities for research in astronomy. Recent work has centered on measurement of north/south comic-ray asymmetries, solar cycle variation of the north/south asymmetry, the implications for certain galactic cosmic-ray phenomena in the solar system, periodicities in cosmic-ray anisotropy related to solar rotation, and cosmic-ray intensity waves for particles in the energy range of from 1 to 200 billion electron volts. In addition, observations of solar cosmic rays have provided new data on the acceleration and propagation of energetic solar particles in the solar corona and in interplanetary space. Northern Greenland has also been important for the study of solar cosmic rays. Observations and analyses of cosmic rays, together with theoretical studies, are leading to an understanding of the large-scale structure of the solar system and of the way that energy is transferred outward from the solar interior.

The polar regions, and particularly the Antarctic, provide a unique platform for studying the earth's space environment. Furthermore, as the sophistication of the technological systems we place in space increases, the need to understand the solar-terrestrial environment also grows. Research in the polar regions can make a unique contribution to this effort to understand the highly complex geophysical environment around the earth.

The NSF program in upper atmosphere physics and astronomy has focused on the Antarctic, with work in the Arctic devoted mainly to observations at the magnetic conjugates of antarctic observational sites. DPP endorsed the Polar Research Board recommendations on antarctic upper atmosphere research and identified a number of future opportunities as guides to planning:

- astronomy in the visible, infrared, microwave, and gamma-ray spectra at the South Pole
- development of ionospheric radars to study small-scale structure
- new conjugate experiments to study wave-particle interactions
- development of automatic geophysical observatories to be deployed in arrays in Antarctica to measure ionospheric and magnetospheric phenomena

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BIOLOGY AND ECOLOGY

The polar regions provide a natural laboratory for studies of ecosystem structure and function and biological adaptations to extreme environments. Such studies advance understanding of ecosystem processes and the biological mechanisms underlying biogeographic distributions and evolutionary relationships. Not only is such science valuable in its own right but it is essential to the management and conservation of living resources of the polar regions and to understanding the impacts of natural and human-induced environmental change.

The Antarctic offers many unique opportunities for biological research, for the Southern Ocean, the world's largest coherent ecosystem, supports a large biomass of invertebrates and vertebrates. The scattered ice-free land areas on the fringes of the continent provide a marked contrast with relatively scant biological productivity.

Unique environmental characteristics of Antarctica include the unusually dynamic sea-ice regions, near-constant sea temperatures close to the continent, and dry, cold, nutrient-poor terrestrial areas. In response to these environmental conditions, antarctic biota have developed special adaptations and life-history characteristics with evolutionary significance. By studying biochemical and physiological adaptations of polar organisms, biologists are learning more about the basis for adaptation to extreme environments at the molecular, organism, and ecosystem levels.

Marine biologists (figure 26) are studying microbiology, seasonal productivity and recycling of organic material during winter, habitat diversity among benthic organisms, extreme depth ranges—from more than 3,000 to less than 10 meters—of selected species, and adaptations to solar periodicity. Other studies are of the availability of organic material and effects of environmental parameters, including pressure and temperature, on membranes and enzyme systems.

The Scientific Committee on Antarctic Research (SCAR) of the International Council of Scientific Unions has been active in promoting marine biology. A 1976 symposium on living resources of the Southern Ocean,

Figure 26. Collecting zooplankton near the Antarctic Peninsula. (NSF photo by William Curtsinger)

sponsored by SCAR and the Scientific Committee on Oceanic Research, led to a 10-year collaborative international research program, Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS). The goals of the program were to advance understanding of the Southern Ocean and its biota and to develop an ecosystem strategy for both exploitation and conservation of antarctic marine living resources. Field studies took place during the early 1980s, and a data center was established in 1985. A major emphasis in the program was research on krill (*Euphausia superba*), a crustacean regarded by many polar scientists as a key organism in the antarctic food chain and crucial to understanding the structure and functioning of the antarctic marine ecosystem.

The Convention on Conservation of Antarctic Marine Living Resources, which came into force under the Antarctic Treaty in 1982, provides a framework for management of living resources of the Southern Ocean, including a long-term program of data collection and monitoring, thus ensuring continuity of the effort begun during the BIOMASS program.

One of the priorities recommended by the Polar Research Board (*Research Emphases for the U.S. Antarctic Program*, 1983) was research to gain an understanding of how the structure and functioning of marine biological communities vary in relation to the ice-edge zone. The NSF-supported project, Antarctic Marine Ecosystem Research at the Ice-Edge Zone, responds to this recommendation. The 6-year study combines physical and biological oceanography and will continue through Fiscal Year 1987, and possibly longer.

A major thrust of the DPP polar biology and medicine program is marine ecology/biological oceanography. The objective is to improve understanding of processes at different trophic levels of the marine ecosystem (figure 27). Knowledge of the relatively simple polar marine ecosystem is expected to contribute to better understanding of ecosystems in general. About 85 percent of the program budget, in both the Antarctic and the Arctic, is allocated to ecosystem research. Most of this research is interdisciplinary and is supported jointly with other NSF divisions. Other research in the program deals with ecology of specific organisms, especially krill (thus complementing and advancing BIOMASS and earlier research on krill), life history patterns and adaptations of terrestrial plants and animals to the environment, and biogeochemical processes (such as nutrient transfer and decomposition) in marine and terrestrial ecosystems.

Compared to temperate and tropical regions, antarctic terrestrial ecosystems are composed of relatively few species that show little interdependence and that have developed special adaptations to deep cold, drought, and long cycles of light and darkness. Biological processes function more slowly in this environment, facilitating the study of ecosystem interaction and interrelationships. The relative simplicity of polar ecosystems suggest that modeling efforts could be productive and should be pursued in future research.

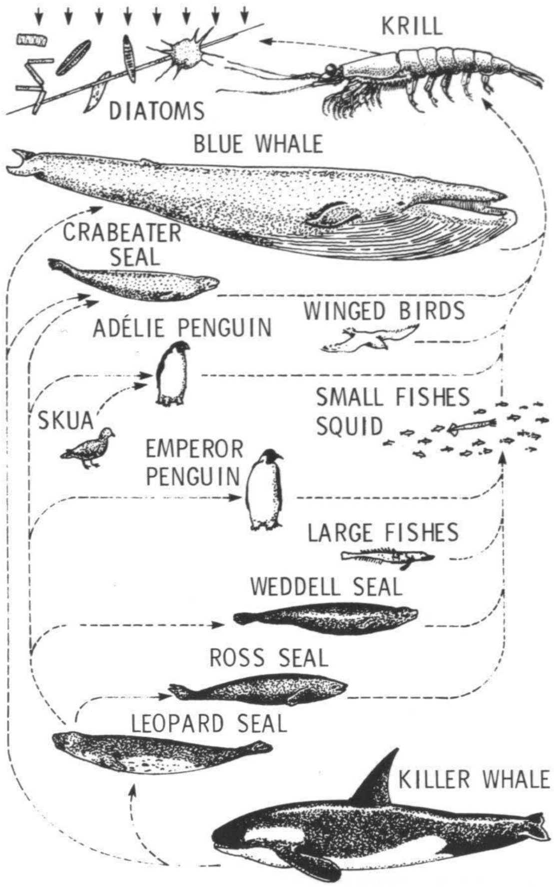

Figure 27. Schematic representation of trophic dynamics.

Antarctic terrestrial paleontology contributes to understanding of the vertebrate paleontology of the former supercontinent, Gondwana. Fossils of lower Triassic vertebrates (reptiles, mammal-like reptiles, and amphibians) have been discovered and show links to fauna in both Australia and southern Africa. The similarities and differences have implications for studies of paleobiogeography and evolution. In addition, the Early Triassic is a critical time in vertebrate evolution, and the antarctic record has a key role in the global assessment of this evolution.

Upper-Cambrian rocks in the Ellsworth Mountains have also yielded a diverse and abundant fauna preserved as shelly material. Included are some 20 species of primitive mollusks, as well as transitional forms that are important in studies of evolution.

In the past 20 years, biologists have made great progress in understanding the molecular mechanisms that underlie many biological processes, especially mechanisms involved in regulating gene action. Over the next decades this knowledge will help to advance understanding of complex macroscopic biological behavior; that is to say, biologists may begin to understand, in molecular terms, the nature of the mechanisms that adapt organisms to cycles of freezing and thawing, light and dark, and rich and poor nutrient environments. These mechanisms, as well as the ability of organisms at different trophic levels to interact, are the result of complex evolutionary processes, which are reflected in the genetic constitution of various organisms. These genes can now be studied by comparing them and their products to homologous functions that have evolved in different environments, especially in extreme environments. Consequently, it is important to understand the precise relationship between structure specified by genetic change and corresponding function. Already, genetic techniques can be applied to classifying and studying various microorganisms that play key roles in nutrient and chemical cycles in polar regions. Some opportunities for applications of genetic engineering to polar species in the near future include:

- mechanisms of enzyme catalysis at low temperature
- cloning of genes coded for enzymes that operate at low temperature or for unique materials that perform well in a low-temperature environment to develop commercial products
- use of the polar regions as laboratories for the study of molecular ecology

A new generation of scientists, competent in both molecular biology and genetics and in ecology and field biology, will need to be trained. Polar molecular biology could lead to understanding (and possibly prediction and control) of complex environmental changes in the biosphere of the polar regions at the molecular level.

In the Arctic, comparative marine ecosystem studies have been hampered by the lack of process-oriented biological data from the central Arctic Ocean. Scientists had assumed that permanent ice cover and low nutrient conditions would result in a generally barren ecosystem. However, satellite imagery shows high amounts of chlorophyll—and presumably high productivity—in open water in the summer. In addition, high production rates have been measured in the ice-edge zones. Studies in marginal ice zones have identified spatial and temporal variations in biological processes and an active food web at all trophic levels. This activity is largely the result of the physical forcing and initial nutrient conditions of the region. In the future, studies focused on the physical/biological coupling in these regions will extend understanding of these productive zones.

The *U.S. Arctic Research Plan* calls for research to improve understanding of the general structure, dynamics, and natural variability of arctic marine ecosystems and prediction of likely effects of offshore oil and gas development, subsistence hunting, commercial fisheries, and other human activities. The Plan recommends a long-term, integrated, multidisciplinary study of arctic marine ecosystems in cooperation with other interested nations.

It outlines needed research programs dealing with (a) effects on biological processes of solar energy variability, ice dynamics, global circulation patterns, and contaminants; (b) population dynamics of mammals, birds, marine fish, and shellfish; and (c) productivity and variability in coastal ecosystems.

The terrestrial portion of the Arctic is largely tundra, taiga, and wetlands. The Polar Research Board has pointed out (*National Issues and Research Priorities in the Arctic*, 1985) that "the physical, chemical, and biological bases of species distribution and productivity need study across a wide range of Arctic ecosystems" (p. 76). The Board recommends research on inland tundra and flowing water, as well as coastal tundra, which is the region most affected by oil and gas development. It also notes that arctic ecosystems are particularly sensitive to annual variations in weather and, therefore, offer special opportunities to study biological effects of climate modification.

The research needs and opportunities in arctic biology and ecology are diverse, urgent, and numerous. The DPP's arctic biology program includes one major project—Inner Shelf Transfer and Recycling in the Bering-Chukchi Seas. Specific marine studies deal with interannual variations in planktonic and benthic population dynamics and productivity, ice-related phenomena, nutrient transport, and adaptations of mammals (figure 28) and fish. In addition, freshwater and terrestrial ecosystem research focuses on experimental manipulation of nutrient conditions in arctic lakes and rivers, food chain dynamics, tundra plant succession, and small mammal population dynamics.

The importance of continuing study of arctic ecosystems is recognized. Further research will lead to prediction of probable impact of global changes in climate and atmospheric chemistry on biota and biotic processes of land and water, as well as the impact of arctic processes on the global climate and atmosphere. Present global climate models predict that the air temperature of the Arctic could rise by 6°C over the next century and that there would be less sea ice. Because the Arctic would experience greater temperature change than would temperate regions, the abundance and distribution of marine, freshwater, and terrestrial biota should be monitored as early indicators of climate change. Other physical and biological interactions that should be monitored include effects of thawing in the upper layers of permafrost, changes in temperature and precipitation on nutrient cycles in soil and vegetation, and climate change on the production of tundra vegetation. Changing temperature and moisture in the Arctic and Subarctic could also lead to an increase in the rate of release of trace gases, especially methane and carbon dioxide, from peats, which could lead to further climate changes. The NSF Geosciences and Biotic Systems Research Directorates are participating in the establishment of biospheric observatories and sites for intensive studies of physical and biological change. These studies could make significant contributions to the proposed International Geosphere/Biosphere Program, expected to get under way in the early 1990s.

Future research emphases in both the Arctic and Antarctic should be on the science needed to fill gaps in current knowledge, such as winter investigations and studies of the central Arctic and western Weddell gyre in the Antarctic, where little data have been collected because of the permanent ice pack. Among the research initiatives that could lead to major breakthroughs in polar biology and ecology are the following:

- use of remote sensing of sea ice together with water color pigments for synoptic imaging of marginal sea-ice zones in the Arctic and Antarctic
- long-term investigations of sea-ice biota (from microalgae, bacteria, and micrograzers to metazoan grazers that inhabit the sea ice itself)
- study of the natural carbon and nitrogen isotope ratios to understand why anomolously light carbon-13 isotopes occur in the biotic components of the Southern Ocean food web
- determination of the extent to which interannual variability in ice cover, solar insolation, and water temperatures influence the Southern Ocean as a carbon sink through biological uptake processes, including primary production and production of biogenic minerals

Future ecosystem research should continue the close interdisciplinary cooperation that characterizes such programs as Inner Shelf Transfer and Recycling in the Bering-Chukchi Seas and Antarctic Marine Ecosystem Research at the Ice-Edge Zone. Such efforts, involving physics, chemistry, and biology, can provide insight into the high-latitude ecosystems, as well as indicating sim-

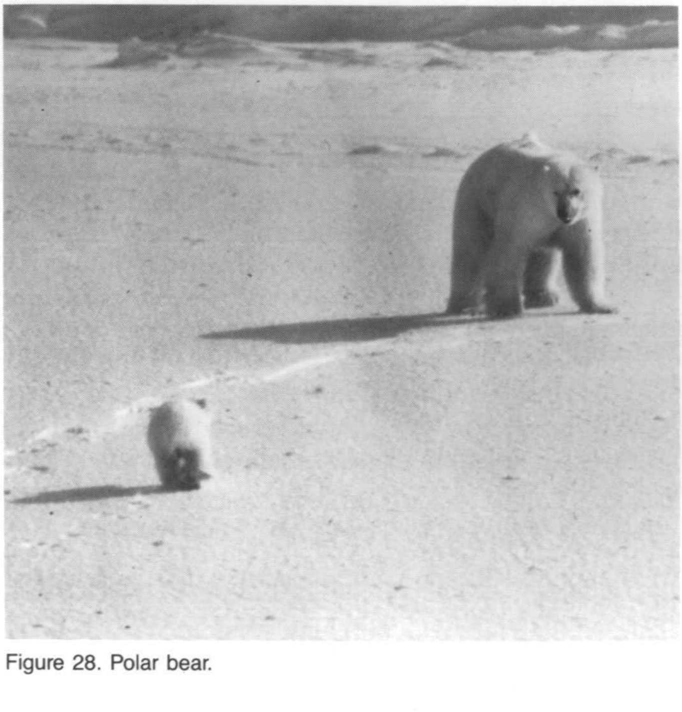

Figure 28. Polar bear.

ilarities and differences between northern and southern hemisphere ecosystem functions and contributing to improved understanding of the global biogeosphere.

The development of new techniques and approaches is essential to achieve research objectives in polar biology and ecology. Such techniques and approaches might include applying the techniques of modern molecular biology, analytical biochemistry, and biotechnology to problems such as adaptations to extreme environmental conditions and structure/function relationships in extreme environments. Adapting laboratory techniques developed in other research areas like flow cytometry and image analysis to questions in polar biology should lead to new advances. A major problem is developing new sampling devices to measure environmental parameters, biomass, and biological processes. The required instruments must be able to withstand the harsh environment and should be capable of continuous monitoring and satellite linkage. Especially needed are instruments that function within or beneath the ice-covered seas. Manned submarines and remotely operated vehicles have not been used widely to collect scientific information except in the defense research community. A major requirement for effective biological research at both poles is a research vessel capable of working in heavy ice cover and equipped for biological field research (figure 29).

Figure 29. British research vessel, RRS *Bransfield*.

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MEDICINE AND HEALTH

Although scientists have not identified any physical disorders unique to the polar regions, polar medical and health research offers special opportunities that provide data applicable in other geographic areas and extreme environments such as outer space. The NSF does not have a basic research program in polar health and medicine, because this field falls within the responsibility of the Department of Health and Human Services. The Department of Defense and NASA also support some polar medical and health research.

Industrial development and population growth in the Arctic has increased the need for the fundamental knowledge and background data to deal with medical and health programs of indigenous population, new settlers, and transient workers. Research in medicine and health is among the highest priorities of the arctic residents. The Arctic Research Commission, Interagency Arctic Research Policy Committee, and Polar Research Board, recognizing this need, have recommended that the particular needs and related scientific questions of arctic residents that should be addressed. The *U.S. Arctic Research Plan* emphasizes that health research should be a basic, integral part of the achievement of national objectives in all the areas defined by the Arctic Research and Policy Act.

The Committee on the NSF Role in Polar Regions has noted this and also a number of recent developments that should stimulate medical and health research in the Arctic. One was the organization, early in 1986, of the International Union for Circumpolar Health, to which all circumpolar countries now belong. The Secretariat is located at the University of Alaska, Anchorage. A second instance of international cooperation and a major breakthrough was an agreement between the Siberian Branch of the U.S.S.R. Academy of Medical Sciences and the University of Alaska to establish a medical research program at the University of Alaska, Fairbanks. Among the major objectives are to establish a center of excellence in circumpolar health studies and a center for the exchange of scientific medical data. Cooperative research is planned on such problems as psychological aspects of adaptation to the far north, mechanisms of adaptive reactions of the immune system in the far northern environment, and biochemical and genetic peculiarities of the effects of alcohol on metabolic processes in Alaskan and Siberian populations. A joint Federal/State of Alaska Task Force on Health Research, established in 1986 to recommend programs for federal and state cooperation, recommended and outlined three such programs—one concerned with injury research (the leading cause of death in all age groups in Alaska), one dealing with patterns in the occurrence of cancer among Native Alaskans, and one to explore the relationship between diet (omega-3 polyunsaturated fatty acids in cold-water fish and marine mammals) and cardiovascular disease.

Because of the high priority generally accorded arctic medical and health research, the opportunities it offers, and the growing need for it, the Committee on the NSF Role in Polar Regions concluded that the present level of support is not adequate and that the appropriate agencies should be encouraged to give greater attention to this field in their future program planning.

Although the Antarctic has no indigenous human population, scientists and others have suggested that the continent provides an analogue for space travel or living on other planets—for example, a Mars flight or Mars base. Thermal regulation, functioning of the immune system, and individual and group behavior during prolonged isolation in a stressful environment are types of research that could be conducted in Antarctica and would have application in a space environment.

Other medical research that can be conducted in Antarctica and that has a wider application is research toward prevention and control of infections, such as the common cold and other respiratory disorders. Those viruses that cause colds are often resistant to many antiviral chemicals and are so varied in antigenic composition that vaccines may not be feasible for the foreseeable future. Studies conducted at two antarctic stations—McMurdo (United States) and Scott (New Zealand)—emphasize the importance of environmental control that can be attained in Antarctica. Major factors in the success of the research were the relative isolation of the human subjects from competing respiratory viruses and control of the subjects' behavior that was possible in this unique "isolation laboratory". The population size of these studies on viral transmission permitted careful monitoring but was large enough to allow statistical analysis. The research began with a small wintering population that was gradually exposed to new arrivals and new sources of inflection. In late August during the winter-fly-in, the population of the two stations increases from approximately 60 to more than 200. During this period, transmission of new viruses was monitored, and intervention techniques tested. Further research showed that rhinoviruses are transmitted by aerosols, rather than through either direct or indirect (through environmental objects) contact. The findings suggested that respiratory virus transmission could be controlled by air circulation—ventilation and filtration system—together with careful nasal sanitation.

An example of the far-reaching medical implications of antarctic physiological research deals with animal extremists adapted for life under conditions that appear incompatible with survival. An antarctic example of this is the Weddel Seal (figure 30). If scientists can understand the biochemical and physiological adaptations that per-

Figure 30. Weddell seals near McMurdo Station, Ross Island. (NSF photo by Ann Hawthorne.)

mit these animals to live in a stressful environment, they may be able to find methods for intervention in analogous situations involving humans. For example, the Weddell seal can dive as deep as 2,000 feet and remain submerged for more than an hour. To cope with oxygen deficiency, the seal has developed a set of reflexes controlling metabolic and membrane functions: breath-holding, slowing of heart rate, and constriction of peripheral blood vessels. In effect, the animal "shuts down" part of its body; other parts—brain, heart, lungs—remain well supplied with oxygen, partially through regulated release of oxygenated blood cells from an enlarged spleen, with preferential distribution to specific organs and tissues. This process is coupled with modification of cell membrane functions so that the cell interior is isolated, the need for maintenance energy is reduced, and cell metabolic rate sharply retarded. The "metabolic arrest" strategy has implications for treatment of oxygen deprivation associated with cardiac arrest, stroke, acute renal failure, lung injury, shock, and organ transplant. However, much research remains to be done to learn how to protect human tissues from lack of oxygen. Research on the combination of cell membrane function and cell metabolism could provide the key to understanding.

Other research, with implications for human health and medicine, includes studies of freezing tolerance in fishes and insects, dehydration among invertebrates in polar deserts, survival for long periods on marginal diets, and voluntary anorexia.

In the Antarctic, the DPP supports medical research as part of its polar biology and medicine program, which emphasizes primarily the biological component. However, in an April 10, 1986, document ("Strategic Planning in Polar Sciences"), the DPP indicated plans for "reallocation of funding to increase antarctic biomedical research."

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BEHAVIORAL AND SOCIAL SCIENCES

In the North, there are diverse and often urgent needs for behavioral and social science research. Yet in assembling information for the *U.S. Arctic Research Plan,* the Interagency Committee found that social science research in the Arctic has low visibility and is poorly organized, administered, and funded (with less than $1 million spent each year). Much of this support is directed toward compliance and environmental impact studies rather than toward long-term fundamental research and does little to advance basic science.

Without a lead agency or a mandated research mission the social sciences have received little attention in most federal agencies. The *U.S. Arctic Research Plan* recommends that social science research of arctic residents, native cultures, and their interactions with the environment be expanded. The results of such research would be useful in planning for industrial development, managing resources, and assessing community needs and social problems resulting from rapid social change. They also are necessary to document the origins, culture, languages, music, art, and subsistence lifestyles of native peoples, to retrieve information on oral history, linguistics, music, art, and other fields where rapid change is reducing the potential data available for scientific research, and to preserve these cultural elements for the future.

The plan notes that in the Arctic there is a better opportunity to understand the interrelatedness of human and natural systems than is possible in most other regions: "If we are going to understand how human societies function and change, adapting to new circumstances, the Arctic is the ideal locus of study." The plan also emphasizes that interdisciplinary approaches are essential in studying the nature of social-environmental relationships and that Native Alaskans should be involved from planning through access to and use of findings.

Research needs and priorities were identified in the following fields: archaeology, social anthropology and ethnology, linguistics, physical anthropology, subsistence lifestyles, geography, history, sociology, psychology, political science, economics, education, and communications. The Arctic Research Commission, the Polar Research Board, and organizations and individuals in the Arctic have vigorously emphasized the need for sociocultural research, which presently is minimal or absent.

In the *U.S. Arctic Research Plan,* highest research priorities are the following problems: social adaptation, economic viability, cultural integrity, resource management, information loss (e.g., from erosion or plundering of archaeological sites or the loss of those people who maintained cultural and linguistic traditions), and geopolitics.

About 20 years ago, behavioral and social sciences research contributed much to personnel selection procedures, understanding of factors in personal and social adjustment and group composition, and performance in polar and polar-analogous environments. Analogous environments, those characterized by isolation, confinement, deprivation, and risk, include nuclear submarines, research submersibles, remote military installations, remote industrial sites, offshore oil rigs, merchant marine vessels, and space vehicles and bases. During the 1970s, however, polar behavioral and social research declined for various reasons, including budgetary constraints, adverse perceptions of such research, and flaws in the methodology of some research projects. Today such research has become more interdisciplinary, quantitative, and performance-oriented and offers potential contributions to more effective operation and improved quality of life in polar and polar-analogous settings.

The Antarctic also provides a natural laboratory for studying the impact of extreme physical conditions on individual and collective behavior. Such understanding will improve safety, productivity, and quality of life in these environments.

Research well suited to Antarctica includes the analysis and modification of management procedures for personnel deployment systems, such as attraction and selection, training, on-site support, and return to community and family. A scale for environmental tolerance might be developed, as well as ways to foster high performance levels, such as modifying architecture to better match work and living environments with behavioral requirements of users. A "Human Spatial Habitability Model" for use in a space station or other compact environment could be developed and explored in Antarctica (Wise, J.A. The Space Station. Human Factors in Habitability. *Human Factors Society Bulletin*, 29 (5), 1986, pp. 1-3). Such a model uses data on the space required to perform certain tasks and variations in the distance between the user and all objects and surfaces that he or she perceives. By modifying design, structure, light, color, and texture, designers and planners can make living and work environments more efficient by making them appear more spacious and hospitable. The model could be useful in designing remote antarctic field stations.

Studies on the behavior of wintering personnel are needed. Long-term, follow-up investigations might be conducted on these personnel, many of whom develop increased self-reliance and ability to cope with stress during their stay in Antarctica. Studies also are needed of the relationship of personality factors to development of the "winterover syndrome" (depression, lassitude, loss of appetite) and cross-cultural studies of adaptation among the scientists and support personnel of different countries conducting research in Antarctica.

The NSF has an opportunity, as lead agency for implementation of arctic research policy and manager of the U.S. Antarctic Program, to foster greater awareness and increased effort in social and behavioral sciences research. This research could advance scientific understanding, help to alleviate or prevent problems of adjustment to the stresses of extreme environments, improve quality of life, performance and productivity, and, in the North, preserve existing sites, culture, arts, and languages and provide new knowledge about the sociocultural heritage of the indigenous peoples.

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ENGINEERING RESEARCH

As the Polar Research Board has pointed out:

The Arctic is a new and extremely difficult frontier environment with major demands on engineering to provide facilities, find and develop resources, provide transportation and communications, and develop infrastructure. Conventional disciplines in engineering are faced with new challenges. New disciplines, such as sea-ice engineering, require further development (National Issues and Research Priorities in the Arctic, 1985, p. 68).

The Board notes that engineering research has a role in all of the issues of national concern identified in the Arctic Research and Policy Act of 1984. These include national defense, resource development, environmental protection, transportation, communication, natural hazards, and health. Engineering disciplines that can contribute significantly to solving problems in cold regions are geotechnical, petroleum, mining, structural, naval architectural, transportation, acoustical, electrical, mechanical, environmental, instrumentation, coastal, and, especially, materials science and ice engineering.

Compared to engineering in temperate regions, engineering practice in polar environments differs because of low temperatures and the presence of permafrost and sea ice. Basic engineering research related to these environmental characteristics, together with field experiments on prototype equipment, is required. As the Polar Research Board states,

Most Arctic engineering problems are very sensitive to scaling error; there are also difficulties in reproducing the full Arctic environment in the laboratory. The Arctic itself must therefore serve for many purposes as the field laboratory for engineering research (Ibid., p. 69).

A detailed presentation of engineering needs and opportunities appears in the report *Arctic Research Needs in Civil Engineering* (Haneman, V. and R. Carlson [Eds.], 1985). This report catalogues needed research in six engineering areas: design and construction of buildings and public facilities, environmental engineering, geotechnical engineering, hydrotechnical engineering, design and construction of transportation systems and facilities, and design and construction of offshore and coastal facilities. Problems requiring research within each of these categories range from less than 10 in hydrotechnical engineering to more than 70 in transportation systems engineering. Priorities are recommended in each grouping. In building design and construction, high priorities are fire prevention and control, waste disposal systems, improved reliability in heating, electrical, and water systems, improved roof systems, and methods for determining performance characteristics and life cycle costs. In geotechnical engineering, among the highest priorities are determining geotechnical characteristics of frozen soils with saline or fresh pore water, studying soil structure interaction at the interface between freezing and thawing ground, mapping subsurface permafrost and ground ice deposits, and studying heat and mass transport in freezing and thawing soils. Major concerns in hydrotechnical engineering are the ice regime of rivers, lakes, and coastal waters, bank erosion, culvert design, construction, and maintenance, and understanding of the groundwater regime in permafrost environments. High priorities for research in environmental engineering include waste water management, solid waste management, air quality and pollution control, and industrial waste management, especially oil-spill response and cleanup. Transportation systems engineering includes pipelines as well as highways, railroads, airfields, vehicles, vessels, and water transportation. Major engineering problems pertain to materials, environmental impacts, hazards, vehicle technology, socioeconomic impacts, and human factors, among others. Recommended research deals with thaw, frost, slope stability, earthquake-induced instabilities in thawing soil, landsliding, flooding, erosion, corrosion, wind, and snow drift. In offshore and coastal engineering, the principal recommended research thrusts included advancing fundamental understanding of: ice mechanics and ice-structure interaction, the sea-ice environment, the marine/soil permafrost environment, coastal processes, and soil mechanics and soil structure interaction. In addition, improved technology to monitor and forecast the arctic environment and improved design methodology for construction and operation of arctic offshore and coastal facilities are high-priority requirements.

These offshore and coastal engineering needs are more fully elaborated in the National Academy of Sciences Marine Board report *Engineering at the Ends of the Earth. Polar Ocean Technology for the 1980s* (1979). This report examines critical engineering research needs related to the identification and development of both renewable and nonrenewable resources, commercial marine transportation systems, environmental data requirements for engineered systems, data acquisition methods, interactions between engineering systems and the environment, and polar ocean logistics. The Board recommended the following:

- initiation by the federal government of a cooperative program to develop the technical capability to support year-round oil-spill cleanup in a range of ice conditions
- establishment of a vessel safety program to develop the necessary technology that would eliminate heavy icing of vessels and equipment and to educate the marine community in safe operational practices in arctic waters
- comprehensive assessment of ocean transportation systems, including the feasibility of a shallow draft icebreaker for use in near-shore areas
- improved remote sensing capabilities to facilitate the conduct of area surveys and to acquire the data for environmental prediction models
- initiation of research on the fate and effects of spilled oil, use of dispersants, and burning of combustible hydrocarbons on ice-covered waters or ice
- definition of the requirements for a family of vehicles capable of transporting personnel, supplies, and equipment to offshore arctic locations
- establishment of a national focal point for identifying, recommending and coordinating solutions to nontechnical, nonscientific constraints on polar resource development.

The *U.S. Arctic Research Plan* gives particular attention to engineering research, especially materials research, a need also emphasized by industry. Among the problems requiring study are low-temperature effects on low-alloy ferretic steels, polymers, and composite materials. For composite materials, research is especially needed on the interface strengths of dissimilar materials and on debonding at low temperature. Freezing and thawing can erode concrete and, consequently, make structures unstable. A rich, high-cost mix is one solution that has been explored; further research could lead to development of less costly admixtures that would function satisfactorily in cold regions. As concrete is a prevalent and basic building material, improving its effectiveness could be greatly beneficial.

The use of heavy materials for construction and other engineering activities in distant regions with extreme environments such as Antarctica greatly increases the difficulties and costs of transportation and handling. Low-cost, light-weight, but strong structural materials need to be developed for use in such cold, remote environments. A special challenge will be materials for the construction of space stations, as well as the design and operation of these stations.

All structures in cold regions, including buildings and warm pipelines, require foundations on natural soil, rock, snow, or ice. The properties of snow, ice, and silt under cold conditions and the phenomena of thaw settlement and frost heave need to be studied further. Such research should include laboratory investigations, physical modeling, numerical modeling, and use of state-of-the-art instrumentation, such as the geotechnical centrifuge. With improved knowledge of the characteristics of frozen ground, engineers will be better able to drill and tunnel in polar regions, as well as to design and construct buildings and pipelines.

To use snow as a construction material in, for example, a runway, engineers must understand its physical properties and ways to improve its strength or other characteristics by using fibers, stabilizers, other materials, and water. Understanding snow mechanics is vital in dealing with problems of slope stability and prevention of or coping with avalanches. For transportation, such snow properties as friction and adhesion to tires of vehicles under different loadings and traction of rubber and other materials also need to be studied. Although deposited

TABLE 1. EXAMPLES OF ENGINEERING RESEARCH FOR POLAR REGIONS

Engineering Need	Problems for Research
Construction	Mode of structure—subsurface, elevated, moveable Roads and runways Site investigation, selection, excavation Pipeline design and mitigation of environmental impacts Drifting snow; snow construction
Facilities	Maintenance of buildings, including heat and vapor fluxes Energy conservation and distribution Water supply and waste disposal
Surface transport	Vehicles—offroad, tracked, air cushion Roads and bridges
Coastal operations	Seabed foundations Ice forces on structures, also a problem in shore Underwater technologies; e.g., pipes and cables
Drilling technology	Design and testing of drilling in frozen ground and ice Fundamental theory for cutting and drilling
Hydrology and culvert design	Design of flood estimation procedures for small arctic watersheds impacted by snow drifts during breakup Development of snowmelt and watershed mathematical modeling methods for low-relief environments (arctic coastal plain) Investigation of methods for selectively weakening ice prior to breakup such as snow removal, dusting techniques, and ice trenching
Containment in frozen soil	Procedures for containment of liquid materials in diked pits
Geotechnical	Review of geotechnical criteria for buried warm pipelines in the Arctic
Instrumentation	Development of deep drilling capability and improved intermediate and shallow drilling technology for glaciological, geophysical, and geological studies, including marine studies of ocean bottom sediments and drilling on continental shelves.

snow is compact and its behavior is to some extent understood, blowing snow creates special problems that affect military operations and defense systems.

The functioning of mechanical equipment at low temperatures presents a broad range of engineering problems. Lubricants, for example, must be effective over a wide temperature range, from ambient cold when not in operation to the temperatures attained during operation. The demands on lubricants under such conditions are severe. Fretting fatigue because of friction in extreme cold is another mechanical problem requiring research.

One of the greatest engineering problems in polar regions is adhesion of ice to structures—power lines, bridges, roofs, offshore drilling rigs, and vessels, for example. Little is understood about the mechanisms of ice adhesion and surface interactions. Also understanding of ice forces on such structures as drilling rigs and ship hulls must be improved.

Besides research to solve problems posed by the low temperatures, the polar regions provide a natural laboratory, which should be more fully exploited, for such problems as the use of superconductors in cold-regions industries.

Table 1 summarizes some of the major engineering research needs in polar regions. The field is so broad and the needs so diverse and urgent that any attempt to summarize is difficult; consequently, the table is a sampling, not a comprehensive list.

At present, because polar engineering research tends to be site-specific and short-term, an expanded data base and ready access to information on previous work related to specific problems are greatly needed. The synthesis of cold region research findings into readily available documents and regular updating of such information would help to eliminate duplicative work and assist the transfer of methods and technology. A special need in this area is to explore how some of the engineering approaches and technologies of the Arctic can be used in the Antarctic.

The NSF, as well as the petroleum industry, have supported a small amount of cold-regions engineering research, but greater effort to stimulate and support such research is warranted. At the same time, the engineering profession should foster awareness of the needs and opportunities in polar regions research and encourage the development of programs in this field in educational institutions. As resource exploration and development and population increase in the polar regions, so too do the needs for housing, transportation, communication, environmental protection, and various systems and services. Trained engineering manpower and innovative approaches to problems posed by the polar environment will become ever more vital to the fulfillment of national objectives in both regions. In addition, opportunities exist for exciting research on fundamental engineering science problems.

LOGISTIC SUPPORT OF POLAR RESEARCH

In polar environments, extensive and effective logistic support is crucial to the science conducted there, and typically, the cost of logistic support exceeds the cost of the science it makes possible, especially in the Antarctic. Although U.S. policy and national interests are key concerns in Antarctica, the inherent intellectual and practical value of science provides the rationale for such large expenditures. If the United States is to fulfill its responsibilities as an arctic-rim nation and a leader among Antarctic Treaty nations, a scientific program of the highest quality—designed for the polar regions—is essential, but science and logistic planning must be closely integrated to make the greatest use of the potential scientific opportunities, supported by facilities and instrumentation.

Although many logistic needs are common to both the Antarctic and the Arctic, the two regions present quite different problems. This chapter deals first with the Antarctic and then with the Arctic and closes with a brief look at a special problem in research support.

THE ANTARCTIC

Sometimes described as "space on earth," Antarctica presents a formidable logistic challenge. Everything related to maintaining human habitation and conducting sophisticated, timely research must be brought into this remote, high-risk environment. Those who have participated in the U.S. Antarctic Program highly commend the DPP on the logistic support it provides through arrangements with the Department of Defense, the U.S. Coast Guard, and a private contractor. Some also have suggested ways to strengthen logistic support and to ensure an innovative, cooperative attitude among scientists and support personnel.

The three U.S. antarctic stations are widely separated and have diverse needs. All are year-round stations that support winter populations ranging from 7 people to more than 100. The DPP logistic objectives in the Antarctic are to maintain year-round occupation and operation of these stations—one interior (figure 31) and two coastal stations, to ensure safe operation in this high-risk environment, to maintain a flexible, productive scientific endeavor, and to set an example among Antarctic Treaty nations.

In Fiscal Year 1986 the expenditure for the U.S. Antarctic Program was $110 million, of which about one-tenth could be regarded as science (if science is narrowly defined to exclude some of the equipment and all of the field costs that typically are covered in a research grant). The program included 129 projects involving 335 people, about the maximum size that the DPP can handle effectively with present staff and facilities. Simply to maintain the program at the present level is expensive, but logistic needs grow as science evolves and as equipment deterio-

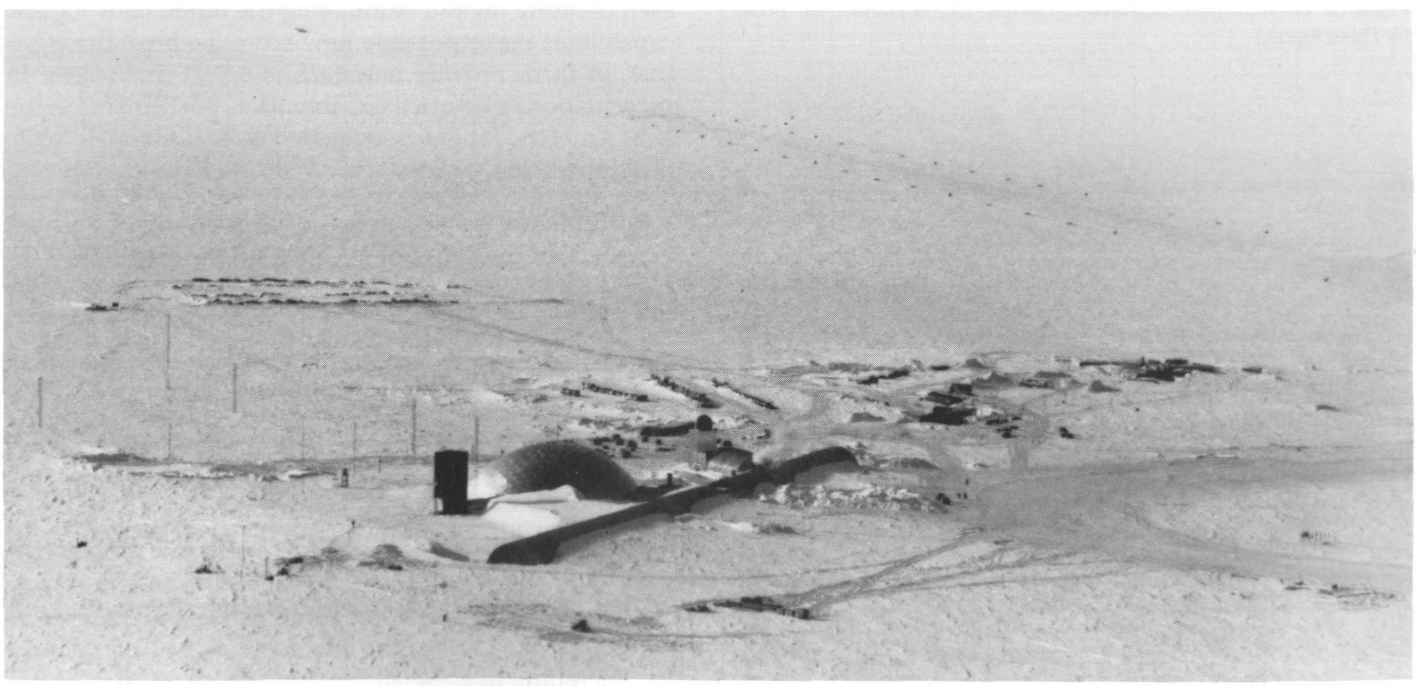

Figure 31. Amundsen-Scott South Pole Station. (U.S. Navy photo.)

TABLE 2. LOGISTIC REQUIREMENTS BY DISCIPLINE (Source: Polar Research Board, U.S. Research in Antarctica in 2000 A.D. and Beyond, National Academy Press, Washington, D.C., 1986). (E = essential; D = desirable)

Facility	Upper Atmospheric & Astronomy Research	Atmospheric Sciences	Physical & Chemical Oceanography	Biological Oceanography	Marine Geology & Geophysics	Continental Geology & Geophysics	Glaciology	Sea Ice Research	Terrestrial Biology	Human Biology
Manned Stations										
McMurdo	D	D	E	E	E				E	E
South Pole	E	E								E
Palmer			E	E					E	D
Siple	E									
Other (including field camps)	E		E	E		E	E			D
Manned Field Stations						E	E		E	
Unmanned Stations										
Land	D	E				D	D			
Ocean (buoys)		D	E		D	D		E		
Balloons & Rockets	D	D								
Satellites & Spacecraft										
Operational (meteorological, ocean)	E	E	E	E	D			E		
Experimental	E	D	E	E		E	E	E		
Shuttle (polar orbits)	D	D	D	D	D	D	D	D		
Ground Stations in Antarctica	D	E	E	E			D	D		
Ships										
Icebreakers			E	E	E			E		
Research vessels		D	E	E	E	D		E		
Drill ships				D		E	E			
Geophysical survey vessels			D		E	E				
Submersibles			D	D	D	D		D		
Aircraft										
LC-130 (cargo)	E	E	E	E	E	E	E	E		
Twin Otter/STOL	D	D	E	E		E	E			
Helicopters				E	E		E	E		
Dedicated "science aircraft		D	D	D	D	E	D		D	
Surface Transportation										
Communications										
Fd. to McMurdo	E	E	E	E	E	E	E	E	E	E
Fd. to U.S. via satellite	D	E	E	E		D		E		

rates. Looking ahead, DPP planners see a number of needs that are becoming more pressing. Although DPP recognizes that the seven fixed-wing airplanes (LC-130s; see figure 32) must be upgraded and eventually replaced, two of these airplanes are already more than 30 years old. The need for a new scientific laboratory at McMurdo (figure 33) has been recognized as essential, and initial funding has been provided. It will cost about $15 million and could be constructed over 3 years, with partial occupation before completion.

One of the greatest future needs on land is a year-round, hard-surface runway and accompanying base, the cost of which would be between $500 million and $1 billion. At sea, the top priority of scientists in government and private organizations in both the Arctic and Antarctic is an icebreaking research vessel (figure 34) capable of providing modern instrumentation and research support. As the Polar Research Board has pointed out (*U.S. Research in Antarctica in 2000 A.D. and Beyond, 1986*), an icebreaking vessel (or vessels) is essential to meet scientific goals recommended in physical, chemical, and biological oceanography, in research on sea ice, in marine geology and geophysics, and in climate research. Such a vessel would also provide support for some atmospheric science research and for research on or near the continental shelves.

Figure 32. Ski-equipped Lockheed C-130 (LC-130) airplane. (NSF photo by Russ Kinne.)

Figure 33. McMurdo Station, Ross Island. (NSF photo by Ann Hawthorne.)

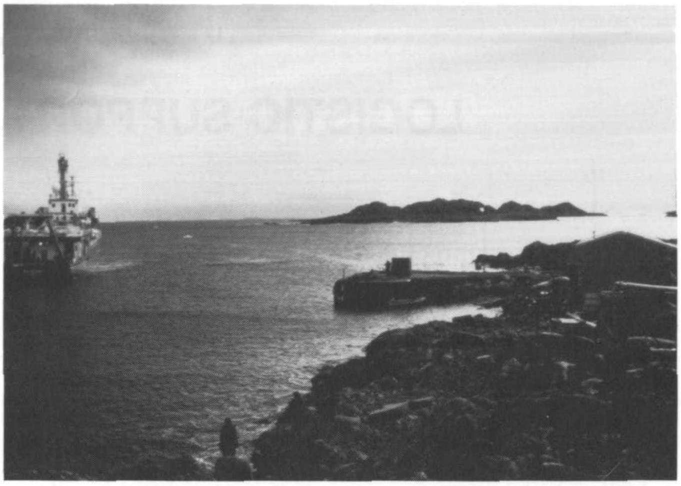

Figure 34. *Polar Duke*. (NSF photo by Don Wiggin.)

Other logistic needs include satellite and other remote sensing systems, automatic weather stations, and deep drilling capability for ice coring and geophysical studies of crust and mantle. Table 2, from the Polar Research Board report, *U.S. Research in Antarctica in 2000 A.D. and Beyond* (1986; pp. 26-28), presents an assessment of logistic support capabilities rated as essential or desirable in 10 fields of polar science.

Science and logistic support are cooperative activities, each building on and stimulating the other. New logistic capabilities make possible new scientific breakthroughs that, in turn, provide new technological challenges. In presentations made to the Committee, participants in the U.S. Antarctic Program suggested ways to enhance logistic support and polar science. Some examples are:

- additional light aircraft, possibly arranged through charter, for support of small field camps
- additional helicopter support (figure 35)
- deployment of more automatic weather stations and of digital recording seismograph stations
- exploration of light-weight materials and new power sources for deep drilling
- exploration of applications of wind power, as in wind-propelled generators
- adaptation of various geologic/geophysical techniques to the special circumstances of Antarctica, including deep-seismic sounding, seismic reflection profiling, and magnetotellurics

Figure 35. UH-1N helicopter. (NSF photo by Russ Kinne.)

- use of submersibles and submarines for oceanography, marine biology, and other related disciplines
- improved coordination with other nations

THE ARCTIC

The northern polar regions have long been inhabited and are the sites of industrial and military activities. Consequently, unlike the Antarctic, systems exist that can meet some of the basic requirements of research support. However, logistic support is in some ways a greater problem in the Arctic than in the Antarctic, chiefly because coordination and funds are lacking. No central organization focuses on or takes responsibility for logistic support. Such support tends to be individually oriented and, in the opinion of some scientists working in the Arctic, less efficient than the logistic support provided by the DPP in the Antarctic. Many federal agencies have programs of arctic research, but each arranges for support of its own activities. University-based researchers have to develop their own logistics for particular projects. Industry, of course, supports its arctic operations, including the research and development. Although the opportunity and desire for cooperative use of facilities and instrumentation exists, meeting these needs has been difficult without a central focus for research and logistics planning. It was suggested to the Committee, for example, that drilling vessels and island drilling systems belonging to the petroleum industry and not currently in use might offer a cost-effective opportunity to undertake research on the ocean floor in the Arctic (Peterson, M.N.A., On Drilling the Arctic Ocean, presentation to the Committee on October 17, 1986). An organization to explore such arrangements and facilitate cooperative use could benefit arctic research.

The lack of a central research support facility has been cited as another difficulty in arctic logistics. Such a facility could support small, movable field camps, as well as ongoing research programs. Also, research equipment and instruments could be stored there at the close of a project or field season, thus facilitating subsequent research and eliminating some of the costs of transporting equipment. It might be used to train technical support personnel, a need stressed by scientists conducting research in the Arctic. In developing the *U.S. Arctic Research Plan* (1987), the North Slope Borough recommended that the Interagency Arctic Research Policy Committee consider establishing a central research facility in the U.S. Arctic. However, federal agencies, including the NSF, have studied the problem and have concluded that the cost of maintaining a general support facility with wide-based operations cannot be justified at this time.

The Canadian system of logistic support has been suggested as a model that the United States might consider. In Canada, one small central organization has responsibility for logistic support of research. It acts as a point of contact, source of advice and expertise, and liaison with native peoples in areas where research is to take place, thereby facilitating cooperation and assistance. The organization tracks field projects and personnel and coordinates and schedules logistic support. Although it is a key part in research planning, the Canadian organization does not own any aircraft. They have found that long-term charter contracts afford a more stable and reliable operation, better pilots, and some cost advantages.

One objective of the Arctic Research and Policy Act of 1984 was to achieve improved logistic planning and coordination in the U.S. Arctic by developing an integrated, comprehensive 5-year plan for arctic research, and by identifying the NSF as lead agency for implementing arctic research policy. The *U.S. Arctic Research Plan* gives specific attention to logistic needs, including satellites and other remote sensing systems (buoys, drifting and moored arrays), submersibles, deep drilling capability for ice coring, ground stations for reception of satellite and other data, and at least one on-site research facility. Also, the Polar Research Board *National Issues and Research Priorities in the Arctic*, 1985), considering logistics needs, stated that:

> *Logistics and support facilities in the Arctic should be improved and their use coordinated in a way similar to, for example, the Canadian Polar Continental Shelf Project . . . there is need for the acquisition (charter or construction) of a dedicated polar research ship and a permanent logistics base in close proximity to the [U.S.] Arctic coast (page 15).*

In regard to a research vessel, the Chairman of the U.S. Arctic Research Commission noted that

> *. . . one can hardly argue for an increased level of U.S. research in arctic waters, either basic or applied, without considering the need for a dedicated research platform flying the American flag. (Oceanus,* 21 (1), Spring 1986, p. 5).

Industry has also recognized the need for an ice-capable research vessel or vessels in the Arctic and, some years ago, collaborated with the federal government in studies of icebreaker design.

In response to growing need and to Congressional mandate, the U.S. Coast Guard has proceeded with plans to replace two of its fleet of four icebreakers (figure 36). These two are nearly 50 years old. In 1984, the Coast Guard assessed all requirements for use of icebreakers by federal agencies and the scientific community and met with users to discuss problems related to scientific support on military icebreaking vessels. Two new U.S. Coast Guard ships have been designed; each possesses a full array of modern, sophisticated research-support equipment and instrumentation. The projected cost of each ship would be $300 million. The first of these ships could be in operation 5 years following the provision of funding, and a second one the following year. The NSF budget request to Congress for Fiscal Year 1988 contains $13 million for the lease and outfitting of an icebreaking research ship to meet the scientific and operational requirements in the Antarctic that cannot be satisfied by existing U.S. Coast Guard vessels.

The acquisition of new icebreaking research vessels by the NSF and the U.S. Coast Guard would place the United States in a position comparable to other nations in its ability to pursue scientific and related goals in both polar regions well into the next century. The Soviet Union, which currently operates two-thirds of the 24 most capable icebreaking vessels in the world, has commissioned a new icebreaking vessel dedicated to research, which will enhance its presence in the Antarctic. The Federal Republic of Germany's *Polarstern* is at present probably the most sophisticated icebreaking research vessel in the world. It operates in both polar regions and contributed much to the success of the field work in the North Atlantic for the international Marginal Ice Zone Experiment. Comparable U.S. capability would enhance international cooperation and complementary efforts in polar research.

A special problem in the Arctic pertains to research conducted in Svalbard (Spitzbergen). Because all arctic geographic zones (for example, polar deserts) are not represented within the U.S. portion of the Arctic, some researchers go to Svalbard to study. When they do so, they are very much on their own with regard to logistic support. It was suggested to the Committee (Ugolini, F.C. The Scientist's Perspective on Arctic Logistics, presentation to the Committee on November 12, 1986) that the United States might explore the possibility of an arrangement with Norway to support scientists working there and perhaps to exchange scientific personnel.

Figure 36. Polar icebreaker. (U.S. Navy photo.)

INFORMATION HANDLING

The *U.S. Arctic Research Plan* and virtually all assessments of research needs in both polar regions emphasize the need for adequate systems to provide awareness of and access to research data and findings. Agreements for information and data exchange are part of the Antarctic Treaty system. A key concern for the SCAR BIOMASS program and for the Convention on Conservation of Antarctic Marine Living Resources was the creation of data centers and related data-handling programs. DPP support of information handling for antarctic research includes curation centers and data products. Curation centers for ice cores, ocean bottom cores, biota, and meteorites are supported. Data-source products include bibliographic control of the world antarctic literature, a research monograph series, translation of foreign polar literature into English, preparation and publication of the *Antarctic Journal of the United States*, preparation of annual exchanges of information under the Antarctic Treaty and the Scientific Committee on Antarctic Research, and maintenance of a polar information program to serve as a clearinghouse and source of information for scientists and the public.

In the U.S. Arctic, research reports often get no further than the "gray literature" of industrial and federal agency technical reports, with resulting problems of awareness and access. The Alaska Oil and Gas Association publishes periodic syntheses, compilations, and descriptions of industrial research projects. The Committee on the NSF Role in Polar Regions suggests that an industrial publication summarizing data and presenting information in a brief report format would be useful to both industry and outside researchers.

The Council on Northern Resources Information Management, in which federal, state, and local organizations are represented, has studied information and data needs in the Arctic and has developed the following set of guidelines:

- improved interagency cooperation in data collection, compilation, and dissemination
- improved awareness and access to both published and unpublished research findings and data
- development of a network to make available scientific information from a variety of sources

- development of compatible standards and formats for data processing
- organization of training sessions and seminars to improve management and use of scientific information.

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Polar Research Board. *U.S. Research in Antarctica in 2000 A.D. and Beyond*. National Academy Press, Washington, D.C., 1986.

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RECOMMENDATIONS

BACKGROUND

The Committee's recommendations derive from the basic research needs and opportunities in the various polar science and engineering fields. Consistent with its charge, the Committee's fundamental concern is what the NSF can and should do to ensure strong, ongoing, high-quality programs of polar research in the Arctic and Antarctic, as called for in statements of national policy. In developing its recommendations, the Committee kept the NSF's scientific mission sharply in focus, as well as its specially assigned responsibilities for basic research in the polar regions.

From its inception, the NSF has been concerned with the well-being of "small" science—the individual researcher, often located in a small institution. Most of the ideas that have had greatest impact on science have come from individuals rather than from large team efforts. However, as the sophistication and cost of instrumentation and facilities required to do high-quality research at the frontiers of science increased, the NSF began to support a number of "big" science programs. In so doing, it did not lose sight of the role of "small" science and the need to maintain balance in the overall basic research program (National Science Board Committee on Centers and Individual Awards, 1987).

The antarctic program has always been a unique type of activity for the NSF. The need to go to a specific location to conduct a specialized research project is analogous in many ways to conducting research at a large accelerator facility or an astronomical observatory.

If the premise is accepted that important science can only be done, or best be done, in a remote location and that such research is in the national interest and is fundamental to the progress of science, then transporting scientists to and supporting their work in the polar regions must be accepted as the price of maintaining vigor and discovery in U.S. science and engineering, as well as a strongly competitive international position.

The NSF has long recognized that the United States has reasons, related to national security, international leadership, and international cooperation, for being in the Antarctic and for doing good science there, thus the Foundation has accepted the logistic costs, which substantially exceed those of direct science support. The principal concern has been to ensure uniformly high quality of the research and, thereby, a leading role for the United States in the international arena of the southernmost latitudes. Recently, the quality of antarctic science has been perceived as comparable to, and in some cases exceeding, the quality of projects in other programs supported by the NSF. In a number of disciplines polar science now offers some of the most exciting opportunities.

In the Arctic, the NSF is one of many agencies supporting research, and its role is not as clearly enunciated as it is in the National Security Decision Directives and White House Memoranda pertaining to the Antarctic. However, the Arctic Research and Policy Act of 1984 offers the NSF the opportunity to take a strong role in arctic research. The NSF mandate to support basic research also strengthens its role in the Arctic where basic research is not the primary mission of other agencies and the need for such research is not fully met. Behavioral and social sciences are obvious examples of fields in which basic research is not sufficient (see, for example, Interagency Arctic Research and Policy Committee, *U.S. Arctic Research Plan*, 1987; Polar Research Board, *National Issues and Research Priorities in the Arctic*, 1985; Polar Research Board, *Polar Biomedical Research. An Assessment*, 1982; and North Slope Borough, *Research Needs in Environmental Science and Engineering, 1985*). Further, the NSF's experience in providing logistic support for the antarctic program affords a foundation of expertise and practical knowledge for leadership in coordinating the present disparate, if not chaotic, and underfunded logistic support of academic arctic research. In addition, arctic research programs should include a strong educational component, which, with its emphasis on science education, the NSF is well able to provide.

The new Global Change initiative in the NSF offers both a rationale and a powerful impetus for increased research effort and involvement in the polar regions, as well as the opportunity to integrate polar science into a broad, global systems-oriented program at the frontier of science. The Committee *strongly recommends that the NSF take the actions necessary to fulfill its role as the lead agency for basic scientific research in the polar regions.*

SPECIFIC RECOMMENDATIONS

There is important science in the national interest to be done in the Arctic and the Antarctic. The NSF operates the U.S. Antarctic Program and has been designated by the Arctic Research and Policy Act to coordinate basic research in the Arctic; therefore, the agency has a primary responsibility for polar science.

1. In both polar regions, research programs must be dictated by the science and engineering needs and opportunities rather than available logistics. The

Committee *recommends that logistics derive from and support the scientific research program rather than dictate that program.* Significant research that can only be done in the polar regions includes, for example, polar effects of global paleoclimates, studies of arctic haze, relationship of interannual variations of sea ice to climate, production and circulation of deep water masses, study of the tectonic role of Antarctica in the breakup of Gondwana, studies of environmentally stressed (extreme cold) organisms, evolution of biological species inhabiting polar regions, and functioning of polar terrestrial and marine ecosystems.

2. The Committee *recommends that the NSF establish and oversee the operation of a network of research support centers for the polar regions.* These centers would be supported by the NSF and managed by universities or private organizations.

3. The Committee *recommends that a logistics program be established for the Arctic to support NSF scientists and research projects conducted in the northern polar regions.* All logistic support facilities and equipment in both the arctic and antarctic programs should be clearly identified as belonging to the NSF and part of the NSF program. The NSF presence and leadership in research at both poles should be visible and recognizable, thereby strengthening the research network through identification with the NSF.

4. As mandated in the Arctic Research and Policy Act, an assessment of research needs for the Arctic and development of a plan to address those needs are in progress. A similar effort should be undertaken for the Antarctic. The Committee *recommends that the NSF take the initiative in coordinating the development of an interagency national polar research plan.*

5. The Committee endorses and encourages the conduct of research in the social, health, and medical sciences in relation to the extreme polar environments and for which the polar regions are uniquely suited. The Committee *recommends that the NSB encourage the National Institutes of Health and other appropriate agencies to support increased health and medical science research in polar regions.* In addition, we *recommend that, in cooperation with such health and medical research, the NSF support basic social sciences research in polar regions.*

6. Further, the Committee *recommends that research on the culture history, linguistics, archaeology, and physical anthropology of arctic peoples be established in the NSF as an identified and appropriately staffed program within the Division of Polar Programs.*

7. Dedicated polar research vessels are an urgent and critical need. The scientific and strategic position of the United States in the polar regions has been seriously, if not dangerously, eroded because the country lacks modern ice-capable vessels dedicated to polar research in the Antarctic and Arctic. Therefore, the Committee *recommends that a research vessel with icebreaking capability be acquired for the U.S. Antarctic Program, and that a research vessel capable of scientific and engineering research in arctic seas also be acquired.*

8. Major logistic components of the Antarctic Program need upgrading, including the McMurdo science laboratories, living quarters at South Pole Station, LC-130s, and helicopters. Private organizations operating on the North Slope of Alaska have acquired expertise in the construction and maintenance of facilities in the polar environment. The Committee *recommends that the cooperation of private organizations and industry be sought in the construction of facilities and provision of logistic support in the Arctic and Antarctic.*

9. The Committee *recommends that health, safety, and environmental protection practices for polar research programs, especially the Antarctic Program, be studied and upgraded where necessary.*

10. The Committee endorses plans for the use of satellites in polar studies and their scientific use as proposed by other agencies. As the recommended interagency national polar plan is developed (see Recommendation 4), the Committee *recommends that other forms of remote and/or automated data collection be funded, and, once in place, fully utilized.*

11. The Committee commends the U.S. Navy's VXE-6 Squadron on the extraordinary job it is doing for the U.S. Antarctic Program. The science could not be accomplished without the dedication, skill, and willingness to serve demonstrated by these fine fliers and support crews. They should remain an integral part of the U.S. Antarctic Program. However, the Committee *recommends that the remaining support functions currently provided by the U.S. Naval Support Force Antarctica be reviewed by NSF management for possible transfer to civilian contractors as suggested by the U.S. Navy, if such transfer proves to be the most efficient and cost-effective option.*

12. The Committee *recommends that the NSF role in the development of polar policy be increased.* The NSF should become more active in policy analysis and decision making on arctic and antarctic issues. Potential policy issues and problems should be anticipated and options for dealing with them developed.

13. Tourism in Antarctica is increasing and can adversely affect the science program. When search and rescue operations become necessary, time, resources, and facilities for planned science activities

are lost, and life and property endangered. Issues related to tourism and responsibility for tourists should be addressed by the Antarctic Treaty Nations; however, the NSF should take a leading role in these deliberations. Stronger recommendations to the Treaty Nations, through the Antarctic Consultative Treaty Meetings, are encouraged. New agreements and procedures are needed; for example, consideration should be given to licensing to assure minimum standards of preparedness, indemnification or bonding, assignment of responsibility to countries for their citizens, and issuance of international visas. The Committee *recommends that national legislation be sought to ensure that tourists are properly insured or indemnified before they visit Antarctica*. Further, the Committee encourages the assistance of nongovernmental groups such as the Antarctican Society, the Explorers Club, and the Alpine Club in developing a voluntary, responsible set of guidelines for tourism in the Antarctic, specifically, and in polar regions in general.

14. The Committee *recommends that basic engineering research be conducted in the polar regions and that it be a specifically targeted research component of such programs to develop the engineering knowledge required for operation in the polar environment*. The appropriate NSF unit to undertake basic engineering research in cold regions is the Engineering Directorate.
15. Finally, and most importantly, because of the exciting and critical science that can and should be done in the polar regions, as shown in the Committee's review of research opportunities in polar science, we *strongly recommend that the funding for polar science wherever it is presently supported within the NSF, be increased to a level twice that budgeted for Fiscal Year 1988 within the next 3 years and that the suggested logistic support be put in place as scientific opportunities and needs dictate.*

APPENDIX

REPORTS MADE TO THE COMMITTEE AND RELATED DOCUMENTS

1) Albert, Thomas F. Perspectives of Arctic Residents on Federal Arctic Research Policy, December 18, 1986.

2) Arnoldy, Roger L. Testimony before the National Science Board Committee on the Scientific Opportunities for Upper Atmospheric Research in Polar Regions, October 17, 1986

3) Baker, D. James. Polar Research Opportunities in the Ocean Sciences - Arctic and Subarctic Oceanography, September 19, 1986.

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