Logistics Recommendations for an Improved U.S. Arctic Research Capability

United States Arctic Research Commission

July 1997

Front and inside covers: View of the ice edge at Søndrestrøm, Greenland from the air (photograph by Richard Alley).

Logistics Recommendations for an Improved U.S. Arctic Research Capability

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Logistics Working Group

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Message from the Chair

Since the earliest of times, as explorers sought to push back the limits of the undiscovered world, the controlling factor in any expedition has been the ability to obtain sufficient support to accomplish the planned mission. We now describe that support as logistics.

In the modern era of discovery the frontiers are not only more complex, they are pushed back almost as far as they can be. Similarly, logistics support is much more difficult and costly. For the last one hundred years the "Achilles Heel" of Arctic exploration and research has been logistic support.

Now, as national governments struggle to varying degrees to control costs, we see emerging a spirit of cooperation in the conduct of Arctic research. The first and most direct application of that spirit in the Arctic is in the area of logistics.

The Arctic Research and Policy Act which established the Arctic Research Commission calls on the Commission to, "recommend methods to improve logistical planning and support for Arctic research..." Toward this objective the Commission requested the Arctic Research Consortium of the United States (ARCUS) to reach out into the Arctic research community for a broad and comprehensive survey of logistics needs.

The accompanying report, *Logistics Recommendations for an Improved U.S. Arctic Research Capability*, provides a community consensus on the priorities for logistics support of Arctic research. The Commission believes that this report is an extremely valuable contribution to our understanding of the nation's needs and logistics resources for Arctic research. We commend those in the research community and especially the ARCUS Logistics Working Group and its co-chairs, Peter Schlosser and Terry Tucker, who edited the report and the ARCUS staff who devoted significant effort to the successful completion of this task.

I recommend that we all use this report as a guide toward executing today's Arctic research in the most efficient manner possible and as a springboard for improving Arctic logistics in the next millennium—more facilities available to all at lower cost and greater efficiency.

George B. Newton, Jr.
Chairman
United States Arctic Research Commission

Foreword

The development and expansion of an organized logistical system for arctic research has been discussed and recommended for more than two decades by a variety of governmental and non-governmental scientific organizations including the U.S. Congress, the U.S. Arctic Research Commission, the National Research Council, the National Science Foundation's National Science Board, the Interagency Arctic Research Policy Committee, the University-National Oceanographic Laboratory System, and the American Association for the Advancement of Science. These organizations unanimously acknowledge the compelling need for expanded research in the Arctic.

The U.S. Arctic Research Commission (USARC) has long been concerned with the state of logistics support for research activities in the Arctic and, in 1995, asked the Arctic Research Consortium of the United States (ARCUS) to assess science-driven logistics needs on behalf of the academic arctic research community and to formulate recommendations accordingly.

To elucidate the particular requirements of arctic scientific research, ARCUS formed a broadly representative working group to assess the logistical needs of U.S. academic scientists. The membership of this working group, as well as the names of community reviewers and contributors, is contained in Appendix B. The specific charge of the Logistics Working Group (LWG) is referenced in Appendix C. ARCUS received funding for the development of these recommendations from the USARC and the National Science Foundation (NSF) Office of Polar Programs Arctic Section. Following an open and extensive consultation process with the academic community (see Appendix D) during which major scientific issues, the logistics requirements to address them, and existing logistical resources were identified, the LWG developed a set of recommendations for the improvement of logistical assets available to U.S. arctic research. ARCUS canvassed arctic researchers in the U.S. academic research community for current and future needs, consulted existing evaluations of logistical needs, and sought wide consultation with the arctic research community and member institutions in the process of developing this report.

The resulting document is a broad survey of multidisciplinary logistics needs that is intended for use by the full range of federal agencies with interests in the Arctic, represented by the Interagency Arctic Research Policy Committee (IARPC). This living document evaluates the limits placed on arctic science by the currently available logistical resources, and endeavors to describe the science-driven logistics needs for the U.S. arctic research community for the next decade with a clear focus on the scientific challenges currently unmet in the Arctic. By bringing the diverse views of the academic community together in this report, these recommendations provide a vital central focus for progress in the support of arctic research.

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Foreword

We would like to acknowledge the many contributions from the arctic research community that have improved each successive draft of this report, as well as the work of the members of the logistics working group. ARCUS deserves acknowledgement for undertaking this important endeavor under the leadership of president Nicholas Flanders. The staff of ARCUS were essential to the successful production of this report. We would like to thank Wendy Warnick for her skillful guidance of the content development and editorial process, Kristjan Bregendahl for his technical expertise, and Alison York for editorial contributions at various stages. Finally, on behalf of the arctic research community, we thank the U.S. Arctic Research Commission and the National Science Foundation for the opportunity given to the arctic research community to participate in this planning process.

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Executive Summary

The Arctic is a region of considerable importance, from both a regional and a global perspective. The Arctic is likely to experience increasing human occupancy and exploitation in the near future, stressing nearly pristine, fragile ecosystems and traditional human societies. The circumpolar Arctic contains extensive reserves of valuable natural resources critical to the world economy. Because it contains a large carbon pool that is being released to the atmosphere, the region plays an important role in global change. These factors require that the Arctic be viewed in both a regional and a global context. This calls for ongoing and comprehensive research in the Arctic and, in turn, a significant expansion of logistical capabilities in the service of the U.S. arctic research program.

Scientific work in the Arctic depends heavily on logistical support. Logistics are the means to access the Arctic and to perform scientific studies within it. Logistics for work in high latitudes are especially extensive, require special technology, and hence, are costly. At present logistics costs claim approximately one third of arctic science funds. A tremendous amount of high-quality research has been done in the Arctic using available logistical assets. The limitations of the existing logistical capabilities, however, have slowed our understanding of larger scale processes in this region. Because of the difficult and remote nature of much of the Arctic, scientists have been "looking for their keys underneath the lamp post" to a certain extent. Investigators have been doing research where and how they could (under the lamp post), not necessarily in the most important places (where the keys might be) or in the most efficient way. Major gaps in our knowledge persist because of inadequate logistical support. Substantial progress will only be made if investigators' logistical needs are identified and addressed. Some of these needed capabilities already exist within federal agencies and programs but many others must be established.

Many areas of the Arctic are not accessible to researchers on a year-round basis. With the current state of arctic logistics, investigators and facilities managers have limited abilities to predict and plan for research opportunities. Many arctic logistical assets are old and need replacement. Often even simple improvements, such as the availability of mobile field camps, would dramatically expand U.S. research capabilities in the Arctic. As science becomes increasingly international in scope, research in the Arctic will become increasingly inefficient without an improved U.S. logistics capability; U.S. researchers will have a decreasing ability to leverage resources from international collaborators and to participate in international research programs.

This report is a broad survey of multidisciplinary logistics needs to improve the capability and safety of the U.S. arctic research program. A remarkable outcome of the community surveys and meetings that formed the basis of this report is the broad consensus among otherwise disparate disciplines in the needs for logistical support. All scientists working in the Arctic will benefit from (1) improved access to research sites, (2) increased development and use of autonomous instrumentation, (3) greater attention to health and safety questions, (4) assistance with involving

The U.S. Arctic remains one of the most difficult places on Earth to do year-round research, with many areas inaccessible in winter.

Executive Summary

Access to the Arctic requires a physical presence to perform certain studies and the ability to deploy instrumentation for measurement of specific parameters throughout the Arctic in any season.

local communities in research, and (5) better international coordination. These five general recommendations outline a coherent logistical support strategy for U.S. research, which is supplemented by detailed, specific disciplinary needs for physical logistics investments. The implementation of the following five general recommendations requires improved coordination within and among scientists, agencies, communities, and nations, as well as the targeted investments in physical logistics assets described in this report which will require expansion of current U.S. arctic logistical support. Extraordinary opportunities may arise in the future which offer a chance to move arctic science and technology dramatically forward with a major investment in U.S. logistics capability. If such an investment benefits multiple research areas and significantly increases the efficiency of data collection, a short-term shift in the balance of funds devoted to research vs. logistics may be justified.

The five general recommendations critical to a coherent logistical support strategy for U.S. research are:

Ensure access to the Arctic over the entire year.

The U.S. Arctic remains one of the most difficult places on Earth to conduct year-round research, with many areas inaccessible in winter. Access to the Arctic requires a physical presence to perform certain studies and the ability to deploy instrumentation for measurement of specific parameters throughout the Arctic in any season. To secure this access, it is necessary to:

- make platforms available that can deploy personnel and instrumentation to land-based sites and the Arctic Ocean and adjacent seas year-round. Platforms that will extend research capability include capable icebreakers, aircraft support, winter housing at Toolik Field Station, and winter-over capability at the GISP2 Summit site.
- provide additional mobile base camps for short- and long-term studies on land, some of which would be available for winter use, including temporary but coordinated logistics support and laboratory space in Barrow, Alaska, and logistics depots elsewhere in the Arctic for the supply and mobilization of field camps.

Increase availability and use of remote and autonomous instruments.

All disciplines require some long-term observations in addition to intensive studies limited in space and time. Many long-term observations are currently provided by manned platforms, which should be replaced with remote and autonomous instrumentation as technology develops. To increase efficiency and comprehensiveness of data acquisition, it is necessary to:

- employ and encourage the development of a variety of remote and autonomous instrumentation systems, including Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), telemetry systems, moored water collection systems, deep floats, monitoring buoys, automatic weather stations, atmospheric samplers, borehole loggers, and remotely piloted aircraft.

- promote adaptation of existing technologies to extreme operating conditions. Increase the spatial and temporal resolution of long-term remote observations.

Protect the health and safety of people conducting research in the Arctic.

Improvements in health and safety will occur with the development of better access; safe and reliable transportation, adequate equipment, and good mobile field camps will remove the *ad hoc* and risky nature of some scientific efforts. Conversely, improved access will also increase the number of people in the field and thereby increase potential risks. The following measures are recommended to better protect the health and safety of researchers in the Arctic:

- Sponsor arctic travel skills and survival courses in cooperation with northern communities.
- Supply, as needed, portable telephone satellite communications, such as INMARSAT (the International Mobile Satellite Organization, the 80-member country inter-governmental organization, also owned by the private and public telephone companies of the respective countries, who market the INMARSAT space segment).
- Identify a provider for cost-effective travel and health insurance to address health emergencies in the Arctic that can involve extraordinary expenses to investigators and federal agencies.
- Establish U.S. bank accounts in local Russian cities to help researchers avoid problems with cash and other means of payment in Russia.

Improve communication and collaboration between arctic peoples and the research community.

Arctic communities are keenly aware of the effects of science activities on their lives and are anxious to learn what science can offer to their understanding of the changes they are experiencing. Although many researchers have long recognized the value in working with local communities, relations with local communities cannot be taken for granted or ignored. This recommendation, as an issue of access and therefore logistics, cuts across disciplines because the location of a research camp in a traditional hunting area is as likely to concern communities as much as the presence of an anthropologist in the community itself. Scientists of all disciplines must be able to interact with arctic communities as appropriate throughout the research process. These interactions could include soliciting community priorities for research, collaborating with communities on research program design, involving communities in the research itself, and discussing the implications of research results with communities. Better physical access will aid relations with arctic communities. Good mobile field camps and year-round research sites will, for instance, create places where local students can participate in educational programs. Still, researchers need assistance to improve cooperation with indigenous communities:

- make researchers working in the Arctic aware of the U.S. Interagency Arctic Research Policy Committee (IARPC) Guidelines for the Conduct of Research

Arctic communities are keenly aware of the effects of science activities on their lives. Residents want to learn what science can offer to their understanding of the changes they are experiencing.

in the Arctic to enhance community/researcher relationships and access of investigators to research sites.

- help researchers establish communication with communities. Identify points of contact in each major arctic region for coordination with communities.
- formalize what has been *ad hoc* and *gratis* logistical assistance from local and regional authorities.
- extend the infrastructure that supports communication among scientists to support communication between scientists and communities. Most important is assistance with the establishment of telecommunications links and on-site equipment that will enable communities to send and receive electronic mail, data files, and documents, and to access the Internet.
- seek guidance to accomplish these goals from trans-national native organizations, such as the Alaska Native Science Commission, the Inuit Circumpolar Conference and the Nordic Saami Council, by direct consultation and inviting them to participate in national and international meetings that address arctic science and logistical issues.

The ability of U.S. researchers to participate in international programs will depend at least partially upon the availability of parallel U.S. logistical capabilities.

Seek interagency, international, and bilateral logistics arrangements to efficiently use all available resources and to reduce costs by avoiding duplication of efforts.

Much of what is needed to support arctic research is already present, but spread throughout federal agencies and among nations. Effective coordination will do much to address the logistical needs of the U.S. scientific community. Implementation of the previous recommendations, especially providing better access to the Arctic year-round, will substantially improve U.S. researchers' opportunities to collaborate and cooperate with international arctic scientists. Currently, such reciprocity is hampered by a lack of parallel U.S. logistical capabilities:

- make the IARPC logistical coordinating mechanism effective.
- fully implement the Arctic Logistics and Information Access and Services (ALIAS) Program.
- convene an international arctic logistics conference to improve communications and identify areas of common interest, and plan for potential collaboration.

Specific priority recommendations are highlighted in the table on pages 62-63.

Arctic field stations (map by Kristjan Bregendahl).

Chapter 1
The Context

Arctic Research and Logistics

The Arctic is a region of considerable importance, from both a regional and a global perspective. The Arctic is likely to experience increasing human occupancy and exploitation in the near future, stressing nearly pristine, fragile ecosystems and traditional human societies. The circumpolar Arctic contains extensive reserves of valuable natural resources critical to the world economy. The arctic region contains a large carbon pool that is being released to the atmosphere; therefore, the region will play an important role in global change. Gaining an increased understanding of the Arctic, both as a region and within a global context, requires a significant expansion of logistical capabilities in the service of the U.S. arctic research program.

Scientific work in the Arctic depends heavily on logistical support. Logistics are the means to access the Arctic and to perform scientific studies within it. Logistics for work in high latitudes are especially extensive, require special technology, and hence, are costly. At present logistics costs claim approximately one third of arctic science funds. These costs are covered directly by the sponsor in large programs or are taken from individual research projects for smaller investigations. In either case, logistics costs alone greatly influence which science issues are presently being addressed. Because of these difficulties, unusual efforts are needed to ensure the presence of U.S. scientific investigators in the Arctic.

A tremendous amount of high-quality research has been done by U.S. scientists in the Arctic with the present limited, often *ad hoc*, logistics assets and arrangements. This situation is becoming one of diminishing returns, as the globalization of science increases and requires a corresponding investment in logistical support. Without an improved U.S. logistics capability, research in the Arctic will become increasingly inefficient; researchers from the U.S. will have decreasing opportunities to participate in international arctic programs and to leverage resources from international collaborators. Much of the Arctic is not accessible to researchers on a year-round basis. With the current state of arctic logistics, investigators and facilities managers have restricted abilities to predict and plan for research opportunities. Many arctic logistics assets are old and need replacement. Often even simple improvements, such as the availability of mobile field camps, would dramatically expand U.S. research capabilities in the Arctic.

Winter field work on the North Slope of Alaska conducted as part of the NSF-funded Arctic System Science (ARCSS) Program (photograph provided by Matthew Sturm).

Chapter 1
The Context

This report on U.S. logistics needs is envisioned as a dynamic plan that will be subject to continuing evolution.

Few dedicated logistical resources are currently available to individual investigators (*i.e.*, social scientists, biologists, geologists) in northern Alaska or the Russian Far East. Many individual investigators are dependent upon their own arrangements and equipment to carry out research. Cold-weather gear, medical preparations, guns, and over-snow transportation may not even be considered as allowable expenses under many funding programs. Attention to safety is quite variable. Investigators working on larger research programs normally have access to more systematic safety precautions. In smaller programs, however, safety issues, whether they involve risk from exposure to arctic weather, bear attacks, or hazardous work at sea, on lakes or rivers in small boats, are frequently left to the discretion of individual principal investigators (PIs). Despite existing levels of technology it is still not uncommon for individual field parties to work in remote regions of the Arctic for days or weeks at a time without adequate radio communications for emergencies. No formal arrangements exist for medical evacuation insurance, and all costs are the responsibility of the PIs and their home institutions. Improved access to safety training, communications, and insurance would improve the safety of small research programs.

This report is a broad survey of multidisciplinary logistics needs to improve the capability and safety of the U.S. arctic research program. The report, envisioned as a dynamic plan that will be subject to continuing evolution, evaluates the limits placed on arctic research by currently available logistical resources, describes the science-driven logistics needs for the next five years, and outlines, with less detail, the needs for the subsequent five years. Extraordinary opportunities may arise in the future which offer a chance to move arctic science and technology dramatically forward with a major investment in U.S. logistics capability. If such an investment benefits multiple research areas and significantly increases the efficiency of data collection, a short-term shift in the balance of funds devoted to research vs. logistics may be justified.

The rest of this chapter describes the context within which the current assessment was made. Chapter 2, *Science Questions*, lays out the scientific questions that arctic research is currently addressing—questions that require logistical support. Specific logistical needs are defined in Chapter 3, *Logistical Requirements*. The recommendations of the LWG are set out in Chapter 4, *Recommendations*. These recommendations are based on the future needs for and the current availability of scientific logistical support in the Arctic.

Science in the Arctic

Logistical support for arctic research is a national interest for many reasons, including the following important issues.

The Arctic may provide strong feedback into the global climate system. Small changes in temperature will affect the extent of the snow and ice cover and, thereby, the amount of the sun's heat absorbed or reflected back into the sky. Thawing tundra releases greenhouse gases into the atmosphere. Increased freshwater fluxes from the Arctic may affect the global thermohaline circulation, with far-reaching impacts. Understanding these feedbacks is essential to describing how the world's climate works. Despite the importance of these feedbacks, most global climate models merely project their results into the high-latitude regions using few actual data to check the models against reality.

The circumpolar Arctic contains natural resources significant to the world economy. These resources include oil, gas, diamonds, coal, gold, zinc, and other minerals. At present 20% of the domestic U.S. oil production comes from the North Slope of Alaska. The Arctic, particularly the Russian sector, contains major oil and gas reserves.

The Russian Arctic plays a major role in that nation's economy. Several large cities are situated north of the Arctic Circle. Resources from this area are important to Russia as it attempts to develop a viable market economy.

The use of the Arctic Ocean for shortened commercial ship transit between the Far East and Europe, with Alaska as an intermediary stop, is currently under study. Ice-dynamics and climate research are essential to a successful operation of this route. At the same time, studies of the potential environmental impact of an active shipping route through these waters have to be carried out together with the economic assessment.

The arctic environment is more vulnerable to long-term and large-scale change than many other regions on the Earth. Species diversity is lower and food webs shorter, so that changes in the abundance of any one species can have significant consequences for the larger ecosystem. Lower temperatures mean that biological processes, such as decomposition, occur on longer time scales. Combined with greater variability in climate, environmental change can be unexpected and long term and may profoundly affect the development of economic resources.

Testing flow rate of an exploratory well during development of the Prudhoe Bay oil field, Alaska (photograph provided by David Klein).

People have lived in the Arctic for more than 10,000 years, adapting to seasonal and interannual changes in the environment. Indigenous peoples have much to teach the world about both the natural environment of the North and how to sustain life in highly variable environments.

The arctic environment is more vulnerable to long-term and large-scale change than many other regions on the Earth.

Chapter 1
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The single most important reason to invest in improved logistical capabilities in the Arctic is to allow research to be planned and conducted routinely, safely, and efficiently, not only by large, well-coordinated programs, but also by small projects and individual investigators.

Many of the animal resources upon which the indigenous peoples of the Arctic rely, such as salmon, geese, whales, and caribou, are migratory, moving north to south in annual or multiyear cycles. These migratory routes cross national borders, puting these animals increasingly under the supervision of international organizations. The indigenous peoples have, as a result, sought a larger presence in national and international management regimes. They have in many cases pointed out the poor knowledge base upon which resource decisions are based, and are helping to improve management regimes.

Contaminants are spreading through the arctic system, and some of them are incorporated into the food chain. Northern communities, traditionally dependent upon local resources, are concerned about the effects of these contaminants. The effects of contaminants may be more worrisome in the Arctic; the Arctic Ocean is largely a closed system and dispersal of contaminants is limited. The shorter food webs characteristic of arctic ecosystems and high fat content of upper trophic levels can cause biomagnification of the contaminants into subsistence foods. Contaminants in the Arctic are becoming a broader concern as they may be found in animals that migrate to and from the mid-latitudes.

Environmental variability is affecting natural resources important to the mid-latitudes. Recent studies suggest that colder waters in the North Atlantic, associated with freshwater discharge from the Arctic Ocean and local atmospheric conditions, may be contributing to the collapse of several commercial and sport fisheries. These collapses have caused problems for national governments because of the need to support local fisheries-dependent communities and to resolve international conflicts over management.

Particularly during winter, cold air masses develop in the Arctic and subsequently travel southward to influence mid-latitude weather. These cold air outbreaks are at present poorly predicted by the numerical weather prediction centers, partially due to the lack of atmospheric observations over the Arctic Ocean.

Science has played, and will continue to play, a substantial role in addressing these complex and interconnected issues. The focus of arctic research must change to address the Arctic as an integral part of the global system. U.S. science efforts in the high latitudes of the northern hemisphere should increasingly focus on the circumarctic region as a whole, requiring improved access to the Arctic and increased international collaboration. Research in the region has, however, been severely limited in the past by the special characteristics of the Arctic. These characteristics have presented logistical challenges, both technological and budgetary. Better access and support will be required for atmospheric, terrestrial, oceanographic, and social research.

To participate effectively in collaborative international efforts, the U.S. must be able to support U.S. research as well as offer logistics capabilities to international colleagues. The single most important reason to invest in improved logistical capabilities in the Arctic, however, is to allow research to be planned and conducted routinely, safely, and efficiently, not only by large, well-coordinated national or international programs, but also by small projects and individual investigators.

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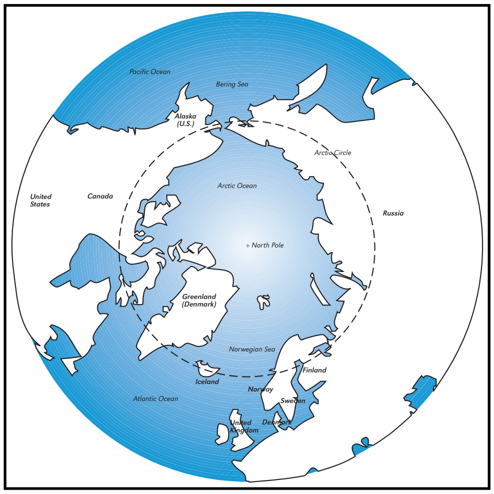
The Context

Geographical Aspects of Arctic Science

Most people know the Arctic to be a region of long, cold winters. Other characteristics are not as familiar, although they have major consequences for working and traveling in the Arctic and the pace at which knowledge of the region can be gained.

The Arctic Ocean covers much of the arctic region and is surrounded by land belonging to Russia, Canada, the United States, Norway, and Greenland/Denmark. From a scientific standpoint, ocean-atmosphere-ice interactions are a fundamental part of understanding how the physical and biological systems of the Arctic work. Research to understand these systems requires platforms for working in waters that are ice-covered for most or all of the year. The ice moves constantly, driven by wind and oceanic currents that we are just beginning to understand in detail.



The Arctic Ocean, surrounding countries, and adjacent seas (map by Kristjan Bregendahl).

Typically, the land that surrounds the Arctic Ocean is tundra and polar desert. Tundra represents special difficulties for travel when not covered with snow. Because of underlying permafrost, water and tussocks create an uneven terrain. Poorly constructed roads, buildings, and pipelines can melt the permafrost, causing major subsidence and damage to the structures. Special construction can avoid permafrost-caused problems, but at high cost. Some land areas are permanently ice-covered, producing unique challenges for safe, effective, and environmentally sound human activities. The vast ice sheets and rocky shores present even more intractable problems.

Despite its image as an uninhabitable wasteland, the Arctic has been inhabited for more than 10,000 years. Today, the communities of the North American and Fennoscandian Arctic are connected to the mid-latitudes through air service, satellite communication, and, in a few cases, roads. Research is both of concern and interest to the residents of these communities. It is of concern, among other reasons, because of the impact any activity may have on local environments and communities. Research frequently has been beneficial, not only because of its findings, but through the jobs and educational opportunities that have been brought into the Far North. To maximize the potential benefits of science and minimize its negative effects, the residents of the Arctic have sought greater participation in all aspects of research.

The Russian Arctic presents a more problematic situation, but one filled with opportunity. Soviet policy sought to develop northern resources for national self-sufficiency and security. Large populations arose in the Arctic. Today, several urban areas in the Russian Arctic have larger populations than all of the North American and Fennoscandian Arctic areas combined. Major scientific facilities and platforms were built in association with these developments. Despite the breakup of the Soviet Union, many important research resources remain. These can be substantial assets, but the situation in Russia also presents challenges to international collaboration.

The Arctic Ocean covers much of the arctic region and is surrounded by land belonging to Russia, Canada, the United States, Norway, and Greenland/Denmark.

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History of Recommendations for an Arctic Research and Logistics Program

The development and expansion of an organized logistical system for arctic research has been discussed and recommended for more than two decades by a variety of governmental and non-governmental scientific organizations including: the U.S. Congress; the U.S. Arctic Research Commission; the National Research Council; the National Science Foundation's National Science Board; the Interagency Arctic Research Policy Committee; the University-National Oceanographic Laboratory System; and the American Association for the Advancement of Science. These organizations unanimously acknowledge the compelling need for expanded research in the Arctic.

Although the desire and opportunity for cooperative use of existing facilities and instrumentation is clearly documented and the need for further development of necessary scientific infrastructure repeatedly published, achieving this has been difficult without a central focus for research and logistics planning.

The Arctic Research and Policy Act (ARPA) of 1984 recognizes the inefficiencies in existing federal arctic research and consequent need for improved logistical coordination and support. The U.S. Arctic Research Commission (USARC) and the Interagency Arctic Research and Policy Committee (IARPC), both established by ARPA, are directed to evaluate the existing federal efforts and to create a program that, in cooperation with state and local governments, would become a meaningful national arctic research program. The ARPA followed up on a 1969 directive issued by then Vice President S.T. Agnew that the National Science Foundation (NSF) should provide the leadership for the development of such a program. While a great deal of time, effort, and numerous publications have been directed toward a coordinated arctic logistics program, this goal is still far from being realized.

The Arctic Research and Policy Act (ARPA) of 1984 recognizes the need for improved logistical coordination and support.

The National Science Board's Committee on NSF's Role in Polar Regions reviewed the earlier documents on these issues and undertook an exhaustive study of arctic research and its logistical support in 1986. The Committee summarized its deliberations in a series of recommendations:

- the NSF establish and oversee the operation of a network of research support centers for the polar regions.
- a logistics program be established for the Arctic to support NSF scientists and research projects conducted in the northern polar regions.
- a research vessel capable of scientific and engineering research in arctic seas be acquired.
- the cooperation of private organizations and industry be sought in the construction of facilities and provision of logistic support in the Arctic.
- other forms of remote and(or) automated data collection be funded, and, once in place, fully utilized.

Existing Arctic Logistics

As noted, the primary purpose of this report is to look at the science-driven needs for academic-based arctic research. An evaluation of these needs requires a consideration of existing arctic logistics assets and circumstances. A more comprehensive description of U.S. and international logistics capabilities in the Arctic is found in Appendix D. What follows is a brief summary of that appendix.

U.S. Logistics for Marine Research in the Arctic

Current U.S. logistics for marine research include ice camps, aircraft, ocean vessels, submarines, and several subarctic research facilities. The U.S. currently has excellent capability for support of drifting ice stations. Stations have been routinely utilized for a variety of oceanographic, meteorological, and sea-ice investigations focused on intensive process studies. Stations can be deployed essentially anywhere in the Arctic Ocean. U.S. commercial and military as well as foreign aircraft have been utilized to support ice camps and deploy autonomous instrumentation over much of the Arctic Basin. In recent years, drifting ice stations have been staged from Prudhoe Bay, Alaska, Thule and Nord Greenland, and Alert, Canada. Prudhoe Bay has also been a staging site for many nearshore marine geotechnical, geological, and sea-ice research studies.

The U.S. has two 399-foot Polar Class icebreakers operated by the Coast Guard. The icebreakers have supported a fair number of oceanography, geology, geophysics, sea-ice, and biology studies. They have proven successful at penetrating deep into the Arctic Basin in the company of another capable icebreaker, but have also demonstrated that their propulsion system is extremely vulnerable in heavy ice. The Coast Guard is currently building the *Healy*, a 420-foot icebreaker whose primary mission is to function as a high-latitude research platform. The 133-foot oceanographic research vessel *Alpha Helix* is owned by the National Science Foundation and operated by the Institute of Marine Science, University of Alaska Fairbanks. The R/V *Alpha Helix*, which is 30 years old, is maintained and used as a year-round platform suitable for oceanographic research on the open ocean and in Alaska's shelf and coastal waters. Its only modestly ice-strengthened hull severely limits its operations in seasonal sea ice and near the numerous tidewater glaciers in Alaska's coastal zone.

U.S. Navy submarines have been successful on three scientific submarine cruises (SCICEX) and have the advantage of accessing virtually any part of the Arctic Ocean permitted by water depth. Currently, the Navy restricts the science cruises to that area of the Arctic Ocean which does not infringe upon the EEZ (exclusive economic

The USCG Polar Sea *during the 1994 Arctic Ocean Section cruise. The U.S. Coast Guard's two 399-foot Polar Class icebreakers have supported a number of oceanography, geology, geophysics, sea-ice, and biology studies (photograph by Lawson Brigham).*

U.S. Navy submarines have been used for studies of hydrography, geochemistry, gravity, bathymetry, and biology, as well as to deploy autonomous instrumentation.

zone) of other nations, but this is still a major portion of the Arctic Basin. The submarines have been used for studies of hydrography, geochemistry, sea ice, gravity, bathymetry, and biology, as well as to deploy autonomous instrumentation.

International Logistics for Marine Research in the Arctic

Canada, Germany, Sweden, and Russia all have excellent research icebreakers. These are not easily available to U.S. scientists. Access to the German and Swedish ships is open only to a small group of U.S. scientists who are collaborating closely with scientists from those countries. The Canadian and Russian ships are available for charter. Norway has commercially available ice-strengthened vessels, which are suitable research platforms in marginal ice zones.

U.S. Logistics for Terrestrial Research in the Arctic

The construction of the Trans-Alaska Pipeline made it possible to carry out research in northern Alaska along the transect of the North Slope of the Brooks Range provided by the Dalton Highway, from Prudhoe Bay in the north, through Happy Valley, to Toolik Lake in the foothills in the south. Much of the research has been supported by the University of Alaska's Toolik Field Station (TFS), operated by the Institute of Arctic Biology of the University of Alaska Fairbanks. The Toolik Field Station is the only national research facility for study of terrestrial biology, freshwater biology, and geology in the U.S. Arctic; it allows major research programs to proceed without the additional efforts required to construct and maintain support facilities. The logistics capability of the Institute of Arctic Biology and TFS gives projects the option of study sites throughout the Dalton Highway corridor north of Fairbanks.

Some research has been based at Happy Valley, at a temporary field station supported by NSF, and using available commercial hotel room and board. Substantial geological and biological research has taken place at or been staged from Prudhoe Bay. Modest hardware supplies, repair services, aircraft services, storage facilities, and room and board are commercially available at Prudhoe Bay. Supplies and equipment can be trucked directly from Fairbanks or Anchorage to TFS, Happy Valley, and Prudhoe Bay.

Research facilities and logistics support are available at Barrow, at the Arctic Research Facility (ARF) of the Alaska North Slope Borough's Department of Wildlife Management, and through Ukpeagvik Inupiat Corporation (UIC, the local village corporation) at UIC-NARL (the former Naval Arctic Research Laboratory) and the Barrow Environmental Observatory (BEO). Study topics include marine and terrestrial mammal and bird biology, botany, archaeology, sea-ice physics, fisheries, and tundra ecology. Recently, the non-profit Barrow Arctic Science Consortium (BASC) has begun to provide logistics support and community contacts for research teams on the North Slope.

Arctic Logistics and Information Access and Services (ALIAS)

Although there are many great successes in U.S. arctic research accomplished with the logistics described above, new challenges (larger field programs related to a system science approach; integration of natural and social sciences) require adjustments of the existing logistics situation towards a modern, efficient, and sustained arctic logistics system accessible to all U.S. academic research institutions.

One effort to address these needs, a logistics information clearinghouse, grew out of the U.S. Arctic Research Commission's recommendations and discussions within the Interagency Arctic Research Policy Committee (IARPC) on how to provide the arctic research and development community with cost-effective support for its activities. The Arctic Logistics and Information Access and Services (ALIAS) is available on the World Wide Web at <http://www.nsf.gov/od/opp/arctic/logistic/start.htm>. The goal of ALIAS is to link existing sources of information from arctic nations, government agencies, universities, and research institutions. The ALIAS home page is still evolving and has excellent potential for assisting arctic researchers.

International Logistics for Terrestrial Research in the Arctic

Greenland

The U.S. currently has extensive logistical support for land-based research (coastal and ice sheet) in Greenland. The U.S. presence in Greenland is supported through international agreement with Denmark. The current U.S. land-based logistical support system is based on open access to and utilization of a combination of Danish government-sponsored research programs, Danish and Greenlandic governmental and civilian coastal and air transportation system infrastructure, the U.S. Department of Defense presence at Thule Air Base, the U.S. Air National Guard heavy-lift, ski-equipped LC-130 air support capability, and U.S. federal agencies' investments in research facilities and support services at coastal and ice-sheet locations.

The ice edge along Søndrestrøm, Greenland (photograph by Richard Alley).

The U.S. maintains several major research facilities and logistical support service contracts to support U.S. research in Greenland. At Thule, the NSF has recently taken possession of a myriad of field equipment previously used for Navy research. In Kangerlussuaq, NSF maintains a radar facility operated under contract with SRI, a field operations center including a warehouse of field equipment, a vehicle fleet and maintenance facility, and seasonal field operations management staff provided under contract by the Polar Ice Coring Office (PICO) of the University of Nebraska–Lincoln. At the site of the recently completed, NSF-sponsored Greenland Ice Sheet Project-Two at the summit of the ice sheet, NSF has maintained under the PICO contract a major camp facility and skiway supporting glaciological and atmospheric investigations. The U.S. currently has the building and camp infrastructure technology available to enhance the Summit site, making it capable of supporting operations year-round.

The Greenland Home Rule-operated Kangerlussuaq Science Center facilities and the Zackenberg Research Station in east Greenland are accessible to U.S. scientists. The library and archives at Ilisimatusarfik (the University of Greenland) and the Greenland National Museum and Archives in Nuuk are also available to U.S. researchers. The Home Rule government has an Office of Research in Nuuk that may be a valuable contact point.

Russia

In recent years some U.S. and European investigators have had successful sea- and land-based expeditions in Russia. Logistical arrangements are almost always difficult to negotiate in the Russian Arctic, however. Due to the lack of Russian science funds, most U.S. investigators must pay for nearly all expedition costs, outside of salaries for Russian collaborators. In recent years, some projects have been asked to pay salary to collaborating Russian scientists as well. Across most of the Russian Arctic, all transactions for food, lodging, or transportation must take place in cash, requiring investigators to place themselves at risk by traveling with large sums of money (up to $10,000-$15,000) on their person. Commonly, U.S. investigators are faced with unexpected costs, such as elevated prices for airline tickets for visitors bearing American passports or new “science fees” created by local government officials. Working in remote regions of Russia usually means working with no radio contact or “safety net” for emergencies. Investigators frequently work without adequate air photos and maps, although this information probably exists. Groups working in Russia have experienced such difficulties as long delays before being allowed to conduct field work, detention, questioning, loss of data, confiscation of equipment, and temporary confiscation of passports by local officials. The success of any research project working in Russia is highly dependent on the networking ability of the Russian research institutes.

Scientists load an inflatable raft onto a local transport vehicle in the isolated village of Enmelen on the southwest coast of Chukotka, Russia (photograph by Julie Brigham-Grette).

Fennoscandia

The research stations in the Fennoscandian countries are supported directly by their governments and are of high quality and capability. Access to research sites in Fennoscandian countries (with the exception of Greenland) is often provided *gratis* or at low cost, but is done so based upon individual cooperative relationships. The lack of comparable U.S. facilities makes reciprocity unusual, which presents ongoing difficulties to U.S. researchers dependent on these relationships.

Norway. Excellent research facilities exist in Svalbard at 79° N under the jurisdiction of the Norwegian government. The Department of Arctic Biology at the University of Tromsø maintains research facilities near the town of Longyearbyen and its international airport. This facility is complemented by the new international teaching and research facilities at the UNIS (University Courses on Svalbard) Building in Longyearbyen, opened in 1993. Collaborative research with scientists from other countries is encouraged, and opportunities exist for year-round research on both terrestrial and marine arctic ecosystems. Ny-Ålesund is a year-round international arctic environmental research and monitoring station in a more remote area on Svalbard that can accommodate up to 150 persons with state of the art facilities. In Norway proper, the northernmost university in the world is the University of Tromsø, which has extensive research facilities and a medical school.

Sweden. Abisko Scientific Research Station is a year-round research facility that can house up to 80 workers. Established in 1903, it operates under the auspices of the Royal Swedish Academy of Sciences and is accessible by rail and road.

Canada

The Polar Continental Shelf Project (PCSP) has provided logistics support for many years for scientists in the Canadian Arctic in a manner that could serve as a model for U.S. efforts. Two base camps are maintained, Resolute on Cornwallis Island and Tuktoyaktuk in the Mackenzie Delta. PCSP provides room and board at its base camps, makes special equipment available on loan, and coordinates the establishment of remote field camps. It provides efficient air transport through long-term chartering with experienced pilots and has a radio communications system through which contact is maintained with remote field camps and aircraft. PCSP supports approximately 200 scientific projects each year. U.S. scientists are able to use PCSP facilities and services on a space-available basis for nominal fees.

Limitations Placed on Science by Existing U.S. Logistics in the Arctic

Despite limited logistical support, U.S. scientists have carried out a tremendous amount of high-quality arctic research primarily resulting from efforts of individual investigators or major programs investigating a single geographic region or disciplinary inquiry. Research in the Arctic has entered a new era, however, including cross-disciplinary, integrated efforts instigated by the system approach to arctic science (ARCSS Plan for Integration 1993), which recognizes that natural processes are interactive, crossing marine, atmosphere, terrestial, and social boundaries. Similarly, understanding global change requires study of the entire Arctic and its role within the global system.

Unfortunately, the logistical support of U.S. science in the Arctic has not kept pace with the recognized research needs. It is well understood that the Arctic will be one of the regions of the earth especially sensitive to global change. Physical, chemical, and biological processes can be modeled and their effects on the human dimension assessed. The models are of little use, however, if the processes are not understood well enough to model properly and if calibration data are not available. The lack of logistics support to carry out detailed process studies and collect spatially and temporally sufficient data to calibrate the models hampers our ability to predict global change.

Currently, major programs oriented around one discipline or region may exclude other important research simply because logistical support is lacking. For instance, important research in the Arctic Ocean requiring an icebreaker which should be conducted annually does not occur because funds for icebreaker support are not available. Similar problems occur in terrestrial, atmospheric, ice-sheet, and social research because transportation costs to research sites are prohibitive. Opportunities for U.S. scientists to participate in international arctic programs are severely hindered because we cannot offer in-kind logistics support.

In most cases, researchers in the Arctic must take their facilities with them.

The arctic region presents major challenges, both technological and financial, to research. In most cases, researchers in the Arctic must take their facilities with them. The cost is not small; a single day of operating a ship in sea ice costs roughly as much as a year's social science research grant. Terrestrial research, mostly based at field stations with high per diem costs charged to individual projects, faces similar challenges. Worthy arctic projects with logistics costs included may compete poorly with research for which logistics are provided separately, at no cost to the project. Adequate logistics support should be extended to all researchers who need it to perform meritorious work.

Finally, the safe conduct of arctic research is a primary consideration. Adequate clothing and shelter are lacking in some cases. Conducting research in the Russian Far East is especially hazardous. Communication is a major issue; even in these days of world-wide cellular phones, it is not unusual for field researchers to be without adequate communications for long periods of time. Provision for emergency evacuations at remote sites is frequently inadequate.

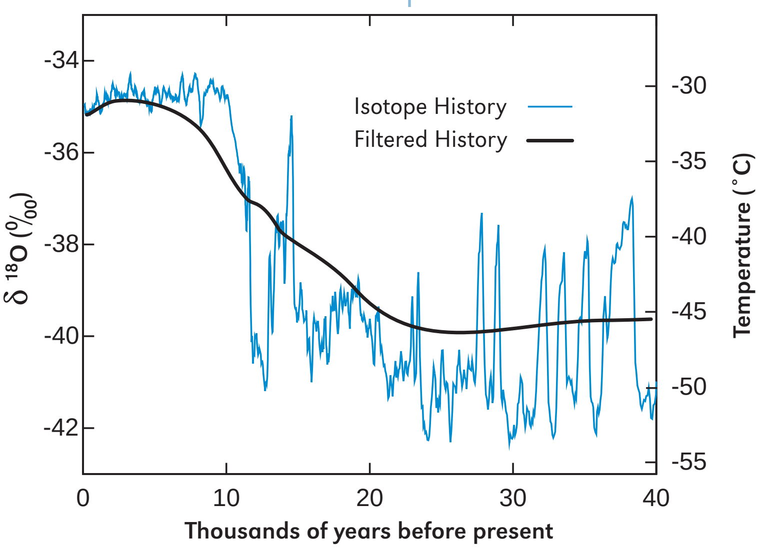
A brackish pond and surplus Bureau of Mines filtration system provide drinking water for the Point Franklin archaeology crew after the advance of summer forces them to abandon the use of meltwater from the top of the Chukchi Sea shorefast ice (photograph by Glenn Sheehan).

Science Questions

The divisions used in organizing the descriptions of important scientific research and the science-driven logistics recommendations in this report are (1) Atmosphere, (2) Oceans/Sea Ice/Seafloor, (3) Ice Sheets and Glaciers, (4) Terrestrial Research, and (5) Cross-Domain Research. These divisions are referred to as disciplines for convenience, although they are largely not true academic disciplines, but rather the domains in which the research of a number of disciplines is conducted. The last, Cross-Domain Research, is a category in which research may be conducted within several domains. These categories arose by identification of common logistical needs within the divisions; the conceptual limitations of such artificial partitioning should be kept in mind. Following are descriptions of important science questions in each of the five domains.

Atmosphere

The arctic atmosphere is a key component of the global atmospheric circulation system; global circulation models predict amplified responses to climate change in the polar regions. These models have poor resolution in the Arctic, and many assumptions are required for processes that are not relevant in temperate regions. The Arctic has little annual precipitation and is classified as a desert. The limited atmospheric cleansing by precipitation makes this region more susceptible to effects of airborne pollution. Recently the phenomenon of arctic haze has been identified as a product of development of industry and cities in the north, especially in the Eurasian sector of the Arctic. How or where these pollutants are removed from the atmosphere and how they interact with arctic clouds, the radiation balance, or the ecosystem are not well understood.



Temperature history from Central Greenland ice cores showing exceedingly large climate changes (Figure from Cuffey, K.M., G.D. Clow, R.B. Alley, M. Stuiver, E.D. Waddington, and R.W. Saltus. 1995. Science *270. 455-458).*

With a well-developed logistical capability in the Arctic, long-term continuity in studies of the arctic atmosphere can be attained. Model simulations suggest that the Arctic is a region well-suited for early detection of climate change. In order to test this hypothesis and to calibrate the global climate models that will guide policy responses to these changes, long-term observations that document the natural variability are required to (1) improve our understanding of the arctic atmosphere, (2) improve the parameterizations of the physical processes in large-scale circulation models, and (3) enhance short-term weather forecasting. They include the following parameters:

- properties of arctic clouds, including cloud-pollution-albedo feedback;
- vertical profiles of atmospheric temperature, humidity, and winds, particularly in the data-void region over the Arctic Ocean;
- surface pressure, temperature, winds, albedo, surface heat flux components and precipitation, particularly in the data-void region over the Arctic Ocean;
- stratospheric and tropospheric air chemistry, including ozone and aerosol chemistry;
- surface fluxes of methane and carbon dioxide over arctic land surfaces; and
- ionosphere and magnetosphere activity.

Oceans/Sea Ice/Seafloor

The Arctic Ocean is the smallest but, nevertheless, one of the least understood of the world's oceans, largely because of the logistical challenges the perennial ice cover presents. The hydrological cycle of the Arctic Basin links precipitation, river runoff, sea ice, and ocean circulation in a single system, the output of which impacts the deep-water formation and the circulation of the Atlantic Ocean. For the past 125 years breaching the sea ice of the Arctic to enable study of these processes has been a central challenge. It was not until the 1980s, however, that European icebreakers demonstrated the feasibility of multidisciplinary expeditions reaching deep into the central basins. Follow-up European and North American expeditions during the 1990s produced surveys at spatial resolution adequate to determine the dynamic features of the Arctic Ocean and provided a first look at many important processes governing modern and past circulation patterns and related climate issues.

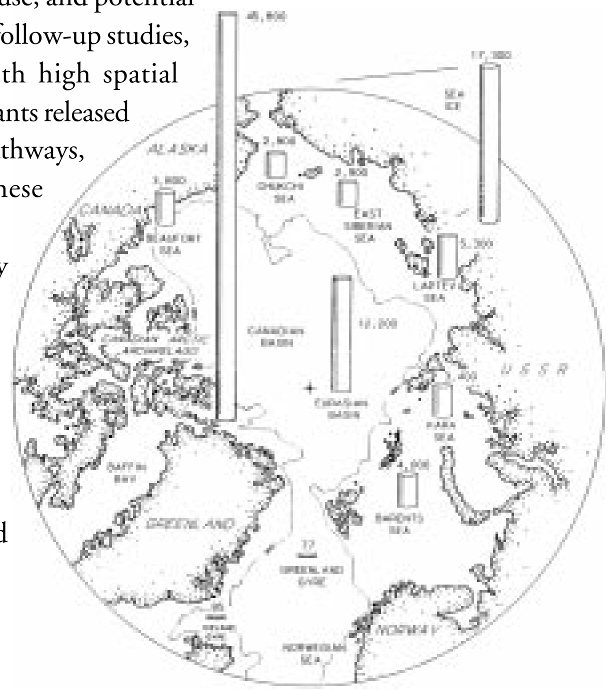
While the ice is a hindrance to surface ships, it has provided ready access by aircraft and has proven to be a stable platform for process studies that are impossible to perform in any other ocean. Drifting ice stations, pioneered by the Soviet Union and later used by Western countries, revealed much of the basic character of the Arctic Ocean circulation: Atlantic Water inflow through Fram Strait and around the eastern margin, clockwise circulation in the Beaufort Sea, and a Transpolar Drift Stream exiting on the western side of Fram Strait. The stations have provided information on how the ice cover evolves over time and interacts with the atmosphere and ocean and have made it possible to measure the small vertical water motions that are responsible for transferring heat and momentum between the atmosphere and ocean. The Soviet Union also pioneered the use of aircraft for hydrographic surveys. From the early 50s to the late 80s the Russian Sever Aircraft Expeditions completed 3800 hydrographic or CTD stations throughout the basin. These have given the Russians a comprehensive picture of the general hydrographic structure and circulation of the Arctic Ocean, which they are now beginning to release to the international scientific community.

Ocean circulation studies

New light has been shed on general circulation patterns by recent scientific observations made on board U.S. Navy submarines, U.S., Canadian, and European icebreakers, as well as by acoustic remote sensing, which suggest there have been changes in the Arctic Ocean circulation. Understanding the cause, and potential links to regional and(or) global climate, requires well-designed follow-up studies, long-term observations, and intensive regional studies with high spatial resolution. Similarly, mapping the potential spreading of pollutants released to the arctic shelf seas requires detailed studies of potential pathways, dilution and scavenging, and mean residence times of these pollutants in the Arctic Ocean.

Although we have a good idea of the basic circulation, many of its mechanisms are still unclear. Furthermore, recent studies have revealed more details of the circulation and exchange patterns in the Arctic Ocean than had been apparent from earlier studies. We now have sufficient information at hand to design appropriate research to resolve these important scientific issues including their variability in time and space. The following specific scientific issues need further detailed studies involving major logistical efforts:

- ❖ surface-water circulation;
- ❖ halocline formation and maintenance;
- ❖ freshwater export off the shelves and its mean storage time in the central basins;
- ❖ major water mass modes, circulation features and sea-ice transport mechanisms and temporal variability on shelves and slopes;
- ❖ frontal systems influencing shelf/basin exchange;
- ❖ (topographically guided) boundary currents;
- ❖ deep- and bottom-water formation and exchange of these waters between the individual basins of the Arctic Ocean, as well as with the Greenland-Iceland-Norwegian (GIN) seas; and
- ❖ variability in all the features/processes mentioned above occurring on time scales ranging from seasonal/interannual to decadal/centennial.



The distribution of freshwater storage in the Arctic Ocean and the Greenland-Iceland-Norwegian (GIN) seas. The placement of each bar indicates the region to which it is applicable (Figure from Aagaard and Carmack. 1989. The role of sea ice and other freshwater in the arctic circulation. Journal of Geophysical Research *94:C10).*

Process Studies

Besides circulation studies, arctic physical oceanography involves studies of processes, both those unique to ice-covered seas and those which occur in all the world's oceans but that can be studied in unique ways in the Arctic. For example, one of the most pressing current issues is the role of the upper ocean in moderating the feedback between atmospheric radiative heating and the reflecting properties (albedo) of the ice cover. Understanding this feedback is crucial to understanding the role of the Arctic in climate. On the largest scales, the positions of ocean fronts at margins of the Arctic Ocean strongly affect the sea-ice extent and thus the albedo of the whole Arctic. On smaller scales, the upper ocean stores heat gained during summer and releases it to the ice at a later time, thus buffering the effect of radiative heating. By controlling the ratio of bottom versus lateral ice melt, the ocean governs how much of this ultimately affects the albedo of the pack ice.

Another important process-related issue is the freshwater (or salt) balance of the Arctic. Climate simulations of the response to increased atmospheric CO_2 suggest that one of the largest signals of climate change may be decreased salinity of the upper Arctic Ocean. The consequences of this may be far reaching because decreased salinity may result in increased stratification in the Greenland-Iceland-Norwegian seas and a consequent reduction of the deep convection critical to the "conveyor belt" carrying ocean heat from low to high latitudes. Although valuable knowledge of mixed-layer processes has been gained in past arctic experiments, no detailed mixed-layer studies have been performed in the summer, which is important to albedo feedback, or in the fall, important to the mixing of fresh surface waters with deeper waters. These are among the following issues that must be addressed:

- physics of the summer mixed layer and its effect on heat storage and the albedo of the ice pack;
- convection processes and the mixed layer during fall freeze-up;
- sources of deep mixing in the Arctic Ocean, tidal generation of internal waves, and the subsequent generation of deep ocean turbulence;
- generation of mesoscale eddies and their role in transporting heat, salt, and momentum in the Arctic Ocean;
- role of the mixed-layer and near-surface processes in the creation of halocline water in the Arctic Ocean and marginal seas;
- convection and mixing on the shelves and the role of these processes in the generation of deep water; and
- monitoring of freshwater inflow from rivers.

The majority of the scientific issues described above in *Ocean Circulation Studies* and *Process Studies* are already included in the science plans of major scientific initiatives such as the U.S. Arctic System Science (ARCSS) Program (ARCSS Workshop Steering Committee, 1990; ARCSS Ocean/Atmosphere/Ice Interactions (OAII) Steering Commitee, 1992), the ARCSS program to study the surface heat balance of the Arctic (SHEBA; Moritz *et al.*, 1993); the U.S. submarine initiative (SCICEX; UNOLS, 1994, 1996); and the international Arctic Climate System Study (ACSYS; World Climate Research Programme, 1994). Successful implementation of these programs depends on the availability of adequate logistical support.

Sea Ice

Sea ice is an important component in the energy exchange between ocean and atmosphere. The uniform ice cover during winter changes to a variegated surface with melt ponds, leads, and bare ice during summer. As ice is melted, a positive feedback is possible with more of the solar radiation being absorbed by the less-reflective surfaces which may increase the rate of ablation. The ice warms, and much of the retained water is flushed rapidly from the ice. Accompanying the warming is a change in internal properties of the ice, which also affects the absorption of solar radiation. The details of this feedback are uncertain. For example, the changes of the radiative surface properties of ice in summer and the ratio of lateral to bottom melting are unknown. The only long-term records of incident solar radiation are from Russian stations. Most of the air-sea-ice process studies have been conducted in the spring when ice camps are relatively easy to maintain. The thickness of the arctic ice cover is crucial to diagnostic and modeling studies of regional and global climate. While remote sensing provides a reasonably accurate portrayal of basin-wide ice extent and concentration, few details of the ice thickness distribution are known. Our current knowledge of basin-wide ice thickness has resulted from analysis of data collected from submarines transiting the ice pack, and, until recently, the majority of these data have been classified. Moored upward-looking sonars also have provided valuable information on the thickness of the ice passing over the sensor. Combined with ice velocity, the ice draft measurements can be used to calculate the advective flux of ice.

Sea ice is known to support an active biological community that interacts with the pelagic and benthic communities but the factors controlling development of these communities are not known. Algae is resident both within the ice and clinging to the bottomside during the spring and summer. Observations indicate that although algae distribution is patchy on central arctic sea ice, it can contribute as much as 60% of total primary productivity. Polynyas are known to be regions of unusually high biological productivity and, despite their small-area extent, probably are major contributors to the total arctic productivity. The reasons for their support of such a rich biota are largely unknown because of the lack of suitable logistic capability for sustained long-term study. Sea ice transports large quantities of sediment from the shallow circumarctic shelves and redistributes it across the Arctic Basin and into the Greenland Sea; ice velocities in the shelf areas, however, are not as well documented as those in the central Arctic. Contaminants, including persistent organics, heavy metals and radionuclides, may cling to the sediment or be incorporated into the ice, and redistributed around the Arctic. Coastal sea ice is also a critically important platform for subsistence harvest activities (see Marine Wildlife Biology, Page 38). Important investigations to be undertaken are:

Sea ice transports large quantities of sediment from the shallow circumarctic shelves and redistributes it across the Arctic Basin and into the Greenland Sea. In addition, algae is resident both within the sea ice and clinging to the bottomside during the spring and summer (photograph by Lawson Brigham).

- ❖ observation and modeling of the energy exchange between the ocean-ice-atmosphere throughout the year;
- ❖ seasonal surveys of ice thickness at selected locations;
- ❖ flux of ice through the major straits between the Arctic Ocean and its adjacent seas;

- effects of sea-ice physics on biology;
- sediment and contaminant incorporation and redistribution by sea ice;
- ice velocities over the outer continental shelves; and
- understanding and predicting changes in the presence and characteristics of coastal ice.

Seafloor

Large areas of the arctic seafloor have not been adequately mapped; only a few continental shelf areas are known from topographic maps at reconnaissance scales (1:250,000 or smaller), although twenty-five percent of the global continental shelf is under the Arctic Ocean. Neither geological nor geophysical surveys have been conducted in many areas to assist in our understanding of the tectonic development and subsequent evolution of the Arctic Basin. The recent release of Russian gridded magnetic, gravity, and bathymetric data, when merged with U.S. and Canadian data to construct digital and hard copy atlases, will be a major step toward solving many unanswered arctic questions.

The seafloor and the continental shelves of the Arctic Ocean contain sediments and ancient rocks holding the answers to many questions that perplex the geoscience community (NRC, 1991), but they have not been sampled because of their inaccessibility. A better understanding of the evolution of arctic climate over the last 65 million years would greatly aid our understanding of the modern ocean-atmosphere system and its sensitivity to future climate change. Existing information suggests that the Arctic Ocean has experienced periods in the recent geologic past when there was little or no sea ice, and other times when the arctic pack ice may have existed only during the winters. We still do not know enough to predict how much warming might make this occur again. The lack of work on sediments recording the continuous evolution of the Arctic Basin through the mid-Tertiary (Eocene to the Pliocene, 55 mya to 2 mya) is a major gap in information. This long interval of geologic time was marked by significant changes in the Arctic Basin as a once subtropical Arctic cooled to become the frigid Arctic of today. Some of the compelling scientific issues that can be addressed via study of the seafloor include:

- petrological composition and structural origin of the major ridge systems (Lomonosov Ridge, Mendeleev Ridge, Alpha Ridge, and Chukchi Borderland) in the Amerasian Basin;
- character and age of the seafloor beneath the Canada Basin and the Makarov Basin;
- geometry, kinematics, and timing of the early evolution of the Fram Strait gateway because the interconnection of the deep Arctic Ocean Basin with the world ocean was an event of far-reaching oceanographic and climatic influence;
- study of the slowly spreading arctic mid-ocean ridge as an endmember of all spreading ridge types;
- comparative analysis of trans-arctic geologic structure and stratigraphy up through the Holocene;

- geophysical and stratigraphic studies of the arctic continental shelves in areas important to understanding their origin and the tectonic evolution of the Arctic Basin;
- focused effort to recover a detailed stratigraphic record of the last 65 million years from several areas of the Arctic;
- role of perennial and seasonal sea ice in glacial/interglacial cycles of the past 900,000 years to understand the processes that drove climate change during the Quaternary; and
- causes of the Arctic Basin's alternation between ice-free and ice-covered states in the geologic past.

Biogeochemistry

The perennial ice cover of the central Arctic Ocean, with its limited irradiance and low temperatures, has led to the notion that it was among the world's most biologically-barren waters. Recent measurements, however, indicate that the Arctic Ocean supports an active biological community and is an active site of carbon cycling. Much of the hydrographic and biogeochemical structure of the Arctic Ocean depends upon ventilation by, and lateral exchange with, waters from the adjacent shelves. The same processes that maintain the halocline also play a crucial role in transporting biogenic materials from the shelf seas to the water column and benthos of the slopes and central basins of the Arctic Ocean. Evidence for global change may be indicated by detectable changes in the size and structure of trophic communities and associated rates of production and utilization. Changes in the lower trophic levels will certainly affect the abundance of fish, marine mammals, and birds and thus their availability to arctic indigenous communities. The understanding of biogeochemical cycles in the Arctic Ocean, and the effects on the higher trophic levels, will require a combination of spatial and temporal process studies integrated with long-term observations in selected regions.

Recent work on global carbon budgets also suggests that inputs from the Arctic Ocean may be the missing component required to balance the large southward export of inorganic carbon from the Atlantic Ocean. Input of carbon from the Pacific Ocean via the Bering Strait and from arctic rivers, and net export of at least part of this carbon from the Arctic into the Atlantic, are potentially important fluxes. Theoretical estimates of the magnitude of these fluxes need to be confirmed by better measurements of inorganic and organic carbon and temporal variations in net fluxes. Evaluation of internal cycling of carbon in the Arctic, as well as exchanges between the Pacific, Atlantic, and Arctic Oceans, will be key areas of work over the next decade. Important areas of investigation include:

- rates and temporal (seasonal) variability of biological production;
- process studies on nutrient and carbon cycling and interactions with phytoplankton, zooplankton, and bacteria;
- food-web interactions under changing environmental conditions;
- characterization of chemical fluxes and cycles;
- transformation rates and concentrations of biogenic materials during halocline formation and temporal and spatial variability;

A researcher sorts a bottom sample from the Bering Sea for biological diversity and composition. Understanding of biogeochemical cycles in the Arctic Ocean, and the effects on the higher trophic levels, will require a combination of spatial and temporal process studies integrated with long-term observations in selected regions (photograph by Lori Quakenbush).

- importance and contribution of each type of primary producer to total annual production and heterotrophic consumption in water column and benthos;
- effect of global change on taxa or trophic structure;
- effect of shelf basin interactions on availability of harvestable marine resources; and
- characterization of chemical fluxes and cycles, including Pacific and river inputs and net export to the Atlantic.

Ice Sheets and Glaciers

Ice sheets and glaciers are of global importance because of their roles in storing and releasing water that affects global sea level and thermohaline circulation, and their storage of long, high-resolution climate records. Additionally, ice sheets and glaciers are of local-to-regional importance because of their roles in water supply, energy fluxes, land-surface processes, and tourism.

Arctic land ice (including coastal Alaska) stores water equivalent to more than 7 m of global sea level, mostly in the Greenland ice sheet. Melting of arctic ice in response to warming in this century is calculated to have been a major contributor to observed sea-level rise, and this trend is likely to continue and accelerate in the future. The record of ice retreat can be used to document the warming and agrees well with other estimates.

The balance of the modern Greenland ice sheet is not known accurately. Little is known about the thickness distribution of many smaller ice masses, and thus their potential to contribute to sea-level rise beyond a few decades. Iceberg calving is poorly understood. Some meltwater produced by warming will be temporarily stored by refreezing in the snow and ice of glaciers; further work on this process is warranted. Fundamental process studies on snow melt, on moisture delivery to glaciers and ice sheets, on ice flow, and on glacial sedimentary systems are needed, supplemented by paleoclimatic work on past forcing and response of the glaciers and ice sheets.

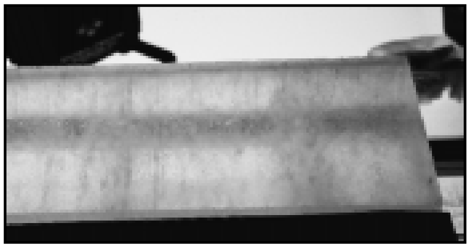
Cores collected from glaciers and ice sheets reveal past climate on local (temperature, snowfall, etc.), regional (dust, sea salt, etc.), and global (atmospheric gases including methane) scales with high resolution over long times (to sub-annual resolution, and to 100,000 years or more). Arctic ice-core data show that climate changes have been larger and faster than previously suspected, that large changes persisted into the modern warm period, and that human industry and agriculture have arisen during times when climate variations were quite small. Comparisons of historical and archaeological records to climate records from lake sediments, tree rings, and ice cores show that even the small, recent arctic climate changes have affected humans significantly. Correlations of arctic ice-core records to records from other parts of the world show that the major arctic climate events have been global and either were driven by or greatly amplified in the Arctic.

Ice cores also document human impacts, including the great rise of pollutants such as sulfate and nitrate. Heavy-metal records from Greenland snow and ice show the effects of Roman lead refining, the onset of the industrial revolution, the dramatic increase in lead pollution associated with the widespread use of motor cars especially after World War II, and the equally dramatic decrease in lead pollution associated with the adoption of unleaded gasoline.

Ice Cores from Greenland and the Circumarctic

The existing ice core records from Greenland provide evidence for past climate changes over more than 100,000 years, with sub-annual resolution for more than 50,000 years. Comparisons between the records from several different cores show that major changes have affected all of Greenland and regions far beyond, but important differences exist between the records as well. The extent to which these differences are local "noise" compared to regional trends related to changes in the polar front and other important meteorological features is not well understood. Differences between the deepest, oldest parts of existing ice cores were caused by ice-flow processes. These differences distort the record of the previous warm period (the Eemian, or marine isotope stage 5e), a crucial time in understanding the predicted greenhouse warming because it had higher temperatures than today.

Ice cores contain a record of virtually everything in the atmosphere, but a great range of indicators has not been exploited fully because of limited samples. Organic acids, biogeochemical markers, trace metals and other pollutants, natural dusts and volcanic ashes, and pollen are present in low but significant concentrations in ice cores and require large samples for accurate analyses, such as determining their isotopic composition to trace the origins of these markers.



Ice core from the center of Greenland's ice sheet (at approximately 1400 m). Two vertical bands, about a third from each end, are clearly visible and represent summer (photograph by Richard Alley).

Ice-core paleoclimatic records are also available from many other ice masses around the Arctic, extending centuries, millennia, or longer. Records in some sites are in danger of being lost as melting of arctic ice masses continues, lending special urgency to these studies. The spatial pattern of climatic change will help reveal the mechanisms involved and will provide clues about how past global changes have been translated to regional scales. One of the most important questions is how future climatic changes will be translated to the regional and local scale, so spatial coverage is of critical interest.

Although no other arctic site can match the combined great length and high time-resolution of the central Greenland cores, similar or higher time-resolution for shorter times is available, and the maximum possible record length is not known for many of the ice caps. All of the studies possible on the central Greenland cores are similarly possible on the shorter cores. Coring on the smaller ice masses can be accomplished with smaller, lighter drills than in Greenland.

Coring sites in Greenland and on the smaller ice masses require knowledge of local atmospheric conditions and air-snow transfer, and offer the opportunity of a wide range of atmospheric studies. Similarly, the ice cores and boreholes provide information on ice-flow conditions needed to understand the ice cores, and the role of the ice masses in sea-level change. Continued site access following coring is needed to extract this information. In summary, the key scientific issues for ice-core records from Greenland and the circumarctic include:

- fidelity of records from deep ice cores on short- and long-time scales;
- spatial variability of climate signals from deep ice cores on the local, regional, and global scales;
- larger sample sizes at key ages (depths) to allow new studies;
- resolution of the paleoclimatic record in the deeper, older ice distorted by ice flow;
- climatic interactions between the regional and global scales; and
- spatial variability of arctic atmospheric conditions and air-snow transfer functions.

Ice-Sheet Dynamics

Much of the observed sea-level rise this century has been caused by melting of arctic (including coastal Alaskan) glaciers, and further sea-level rise is projected from these sources. The 7 m of sea-level locked up in the Greenland ice sheet represents a potentially huge impact on the Arctic and the rest of the globe. Global-warming models including arctic enhancement of changes project strong melting of Greenland ice, contributing to or dominating future sea-level changes and perhaps affecting the global oceanic circulation through freshening of the North Atlantic. The local impacts of changes in alpine and coastal glaciers are well-known, including surges that cut rivers and form lakes which may flood surrounding areas, and which may then drain catastrophically and flood downstream regions. Mountain glaciers provide a laboratory in which ideas on glacier stability and dynamics, and on glacier sedimentary systems, can be tested before they are applied to understand the aquifers of the northern U.S. and to help predict the future of the Antarctic and Greenland ice sheets. Deglaciation reveals land surface that usually is covered with physically abraded, fresh mineral surfaces that then weather rapidly, affecting chemical fluxes. The records of deglaciation provide paleoclimatic information. Snowfall on mountain glaciers is strongly impacted by local conditions including the existence of the glaciers themselves and is not well-represented in modern atmospheric models, raising questions about future projections of sea-level change. Large uncertainties on small glaciers as well as the Greenland ice sheet are related to percolation/refreezing of the meltwaters, energy exchanges at the ice surface and its interaction with the atmosphere, and flow and calving response of the ice mass. The key scientific issues related to ice dynamics processes in Greenland include:

- characteristics of the newly discovered northeast Greenland ice stream and its significance for ice-sheet stability;
- current mass balance of the ice sheet; and
- energy and mass fluxes at the surface and the margins of the ice sheet.

For arctic alpine and coastal glaciers, the key issues include:

- individual and circumarctic glacier ice volume and area, and their rates of change, for prediction of sea-level changes;
- increased sampling to assess how representative the limited available data are for the great range of circumarctic glaciers; and
- spatial patterns of ice-atmosphere, ice-ocean, and ice-sediment interactions.

Terrestrial Science

Chapter 2

Science Questions

The landscapes of the Arctic offer unique opportunities for research in biology, geology, and paleogeography. Arctic terrestrial life is limited by a short growing season, low temperatures, and low rates of nutrient cycling; more information about how plants and animals have evolved in these extreme conditions will improve understanding of the capacities and limitations of physiological systems. The relatively simple and undisturbed ecosystems of the Arctic provide valuable models for investigators interested in a range of questions from ecosystems through wildlife biology to animal behavior. Biological communities in the Arctic will be sensitive to predicted higher temperatures which may affect the harvest of plants and animals by humans.

Arctic terrestrial surficial processes are also limited by low temperatures and are modulated by changes in the duration of frost cycles, the depth of snow, and the hydrology of rivers, lakes, and streams, for example. Arctic soils and peatlands serve as important sources and sinks of global carbon dioxide and methane. The processes that control the net uptake or release of these gases involve strong biotic feedback and appear to respond sensitively to local changes in soil moisture and temperature. The thawing of permafrost affects terrestrial hydrology and water balance; permafrost thawing may also increase the availability of soil nutrients to plants, while improved drainage and nutrient cycling may lead to an increase in nitrogen and phosphorus loss from the soil to rivers, lakes, and oceans.

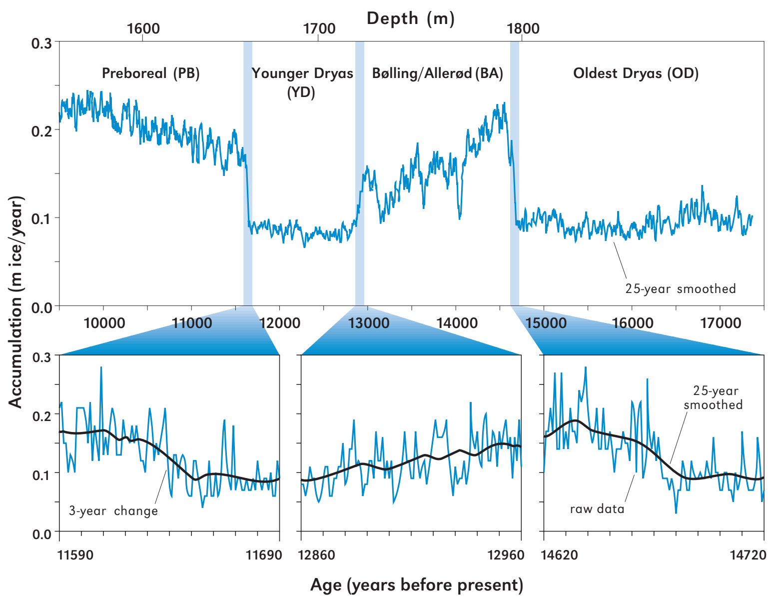
Studies of modern processes are key to understanding the richness of the paleoclimate archive preserved beneath the tundra, in coastal and river bluffs, and in lake systems. Paleorecords provide crucial information for evaluating the accuracy of various models (*e.g.,* atmospheric, oceanic, and ecosystem) and for developing predictive models of future climates.

Caribou are a widespread arctic species that migrate long distances each year; biological communities in the Arctic will be sensitive to predicted higher temperatures which may affect the harvest of plants and animals by humans (photograph by Robert White).

The modern climate system of the Arctic is highly variable as demonstrated by past and present data sets from widely spaced, instrumented sites. Regional studies across climate transects are just beginning to provide information concerning the effects of coastal versus inland locations. However, what is known of the modern climate is circumscribed by the sparse nature of the instrumented stations. Recently, scientists have begun to synthesize this limited information in order to understand how feedback processes amplify global climate change. The first step is to learn how to predict events in the Arctic at larger scales of space and time. Modeling has begun on permafrost processes, snow distribution, hydrology at watershed and pan-arctic scales, as well as biological phenomena at the regional scale. Many models are designed to predict the effects of changes including climate and human-induced changes (*i.e.*, land use, eutrophications, harvesting of animals) on the tundra and its organisms. The following scientific issues need further studies involving major logistic efforts.

Climate and Paleoclimate

Large-scale models based on available data provide important insights into how the climate system operates. How sensitive this system is to even subtle changes (*e.g.*, changes in ice extent, cloud cover, or ocean temperatures), however, is not understood. Studies of climate change on a global scale show that the ocean/atmosphere/land system in the North Atlantic, for example, is capable of switching from one climate mode to another on time scales of less than 40 years. Recent work shows that such changes are recorded in every ocean basin suggesting nearly instantaneous global responses. What can drive these mode shifts, how sensitive the arctic system is to such fundamental changes, and how these impacts influence climate at lower latitudes is still poorly understood. Studies of past climate modes and shifts provide critical data on the nature of the response of the arctic system to past climate changes, as well as the full range of natural variability. Such data provide tangible evidence of what the Arctic may be like with even modest future global warming and a reduction in sea-ice extent. To fully understand and model more accurately the spatial variability of the natural climate system, both regional studies and east-west transects are needed.



Accumulation-rate history of Central Greenland from GISP2 ice-core data, showing that exceptionally large climatic changes occurred over very short times, as little as one to three years (Figure from Alley, R.B., D.A. Meese, C.A. Shuman, A.J. Gow, K.C. Taylor, P.M. Grootes, H.W.C. White, M. Ram, E.D. Waddington, P.A. Mayewski, and G.A. Zielinski. 1993. Abrupt increase in snow accumulation at the end of the Younger Dryas event. Nature *362. 527-529).*

- ❖ High-resolution studies of past climates of the last 20,000 years, particularly studies of well-preserved lake sediment archives, are necessary to provide essential information on how the system has operated in the recent past.
- ❖ Lower resolution studies of sediment and fossil archives preserved in coastal bluffs, river bluffs, lakes, and broad basins on land are needed to provide longer records of past climate (0 to 2 million years old) indicating the range of natural variability in the climate system. For example, it is necessary to study sediments as old as 125,000 years to assess the climatic conditions of the Arctic when temperatures were slightly warmer than they are at present.

Response of Biogeochemistry, Hydrology, Permafrost, and Thaw Depth to Change

Movements of water and energy through the soils and vegetation of the tundra affect biological processes, as well as control feedbacks to the atmosphere. All aspects of life on the tundra are affected including the flux of trace gases from the soil into the atmosphere and the transfer of water, nutrients, and organic matter from land to the Arctic Ocean. Important areas of investigation include:

- A predictive model of the hydrology cycle should be developed for an understanding of what will happen to soils, animals, plants, and oceans when the environment changes.
- The effects of permafrost melting on CO_2 and CH_4 release or uptake need to be understood.
- Both models of annual thaw depth throughout the Arctic and of how permafrost heat transfer will proceed given a range of climate change scenarios needs continued development.
- Snow redistribution is an active process throughout the Arctic. Models are needed that will use precipitation, climate information, and topography to simulate present and future distributions.

Basic Studies of Tundra Biota

The emphasis on understanding the whole terrestrial biotic system has brought to the fore a number of research areas where little is known or where engineering and scientific developments now allow large increases in understanding.

Physiological studies of arctic animals in their natural habitats are now possible because of miniaturization of sensors of internal temperature or of blood flow. A tiny temperature recorder can now be implanted into the arctic ground squirrel, for example, that will record body temperature during hibernation. Reproduction, stress, foraging dynamics, energetics, and thermoregulation need to be studied year-round.

Studies of the movement of large, free-ranging animals are now possible through the use of global positioning systems (GPS). Activity of caribou, polar bears, and muskoxen can be monitored from signals transmitted from the animals to office computers via satellite. Scientists will be able to address questions about the movement of animals in response to local conditions of climate and snow in ways never possible before.

The location and extent of snow cover are important to the distribution and survival of many plants and animals. Past studies have correlated the distribution of small animals and plants with snow cover. Now the next generation of questions needs to be asked as to the effect of a reduction or increase in snow cover on the biota.

The soils of the Arctic are the site of tremendous stores of organic carbon, which might be converted to CO_2 gas, and of organically bound nutrients. Consequently, changes in soil temperatures may strongly affect the nutrient supply to plants in the future. The soil biota, community structure, fluxes of gases and nutrients, and the controls of processes such as decomposition need to be evaluated to completely understand crucial ecosystem processes.

Response of Biotic Communities to Change

When environmental conditions change, organisms change their productivity and distribution. Changes in structure and function of ecosystems can be triggered by human harvesting of animals, both in freshwater and on land. These changes need to be monitored to determine if biotic change is occurring now. In addition, process studies and large-scale manipulation experiments need to be carried out to predict the result of future and cumulative changes ranging from climate to UVB.

At a number of local sites across the U.S. Arctic, there now exist long-term records of observations such as the data from the Arctic Long-Term Ecological Research (LTER) project at Toolik Lake on plant flowering and production, lake temperatures, and stream biota. Long-term data also exist on effects of oil field development on caribou and nesting birds. Data on the CO_2 in the atmosphere at Barrow over decades reveal a biotic response to warming and drying of the climate. Some specific studies include investigation of the processes controlling hydrology and freshwater runoff; ecological studies of plant and animal populations, communities, and ecosystems; the effect of climate change on permafrost formations; and trace gas fluxes (CO_2 and CH_4). Long-term monitoring is needed to separate the natural changes in plant distribution, in plant communities, and in treeline location from the response to climate change.

Researchers weed experimental plots at Toolik Field Station, Alaska to examine plant competitive relations (photograph provided by Sarah Hobbie).

Experimental manipulations of tundra, streams, and lakes must be continued and expanded into several different types of arctic environments. This is the only way to test how biotic processes will respond to changes and the best way to develop data for calibration of models of future effects. Time-depth information can be added to these manipulation studies by examination of previous human-induced changes, (*e.g.,* numerous tundra ponds connected by shallow ditches to avoid portages; previously artificially drained ponds and lakes in and near the Barrow Environmental Observatory; naturally drained ponds and lakes, such as those apparent in comparison of modern Pt. Franklin to 1949 archival aerial photographs).

A long-term goal of environmental modeling in the Arctic is to simulate and predict processes, such as trace-gas release or ecosystem productivity, over the spatial scale of the entire Arctic. To do this, measurements of selected key variables are necessary in diverse samples of arctic ecosystems in order to extend the models to the coarse scale. Much of the information on processes in arctic ecosystems has been developed at two or three sites. The geographic range of such studies needs to be expanded across landscapes, watersheds, trophic levels, and into different types of arctic systems.

Understanding the interactions among atmospheric conditions, wildlife, and human behavior requires information on the frequency of episodic weather events and changes in mean temperature and precipitation measured with regional resolution (10 to 100 km). The frequency of icing and snow crusting events needs to be modeled. Existing data series for temperature, precipitation, and wind do not adequately measure important differences between coastal and inland conditions.

The effect of a possible increase in the amount of UVB solar radiation should receive more investigation. Little is known today of the importance of current levels of UVB, and studies of the current role of UVB should receive first priority. These should be expanded to include studies of experimental enhancement of UVB and its effects on stream biota, lake chemistry (especially on dissolved organic carbon), terrestrial plants, and individual organisms including humans.

Feedbacks Amplifying Global Change

Some processes of the Arctic, such as those involving clouds and moisture, snow and ice albedo, and trace gases, may amplify global climate change. Research will improve understanding and allow better numerical model results and predictions. To evaluate these feedback processes, estimates are needed of the total rate of selected processes and fluxes for the entire Arctic. Most of the field measurements have been made on small plots of several square meters. In the future, sampling strategies should be used that will determine the appropriate scale for regional estimates.

- ❖ Trace gas fluxes at the square meter scale should be scaled up to the hectare and square kilometer scale.
- ❖ Estimates of vegetation distribution, seasonal snow cover, and soil moisture should be made over entire regions with remote sensing.
- ❖ Albedo studies that include the effects of aerosols and soot on radiation and energy balances should be undertaken.
- ❖ Studies of cloud/haze interactions and microphysics of arctic clouds are necessary.

Coastal Geomorphology

The arctic coast is a natural battleground between the land and the sea where storms, sea ice, and long-shore drift constantly reshape the interface. The Alaskan Inuit have lived at the coast for millennia, making use of the ocean's rich resources while moving camps as storms recreated the land. Today many arctic communities are in peril because their permanent coastal townsites are threatened by coastal retreat. Harbors and bays are repeatedly dredged to keep waterways open and maintain local fishing and shipping economies. Prospects of amplified warming in the arctic regions may mean an increase in the open water season when the coastline is most active. Studies of coastal processes in all seasons at a variety of sites would provide important data on the natural system and determine rates of retreat and natural replenishment. These data are needed to provide critical planning information for the mitigation of coastal erosion—resolutions that sometimes call for moving entire villages inland, such as the plans for Shishmaref or Kivalina, Alaska, or for long-term dredging and beach replenishment, such as at Wainwright and Barrow. In addition, this information could provide sound community guidelines regarding future development of the coast or, for example, the long-term implications of municipal or private mining of nearby beach materials for roads or other construction. Such issues of geomorphology are also social issues of immediate concern to villages and towns. Improved logistical access on a year-round basis to many coastal areas would facilitate:

- Studies of the historical use of the coast as well as archaeological records of human occupation of the coasts. These data provide information about the cultural and natural history of the Arctic, a record that will soon be lost due to coastal erosion in many areas.
- Studies of coastal processes and river-mouth sedimentology, especially coastal sediment supply and erosion on an annual basis.

Other Issues in Geology and Geophysics

Terrestrial geoscience programs range from regional tectonics and basin analysis relevant to the evolution of mountain systems, the origin of the Arctic Basin, and location of petroleum and mineral reserves, to studies of surficial deposits for understanding past climate change and the frequency of natural disasters (earthquakes, tsunamis, and volcanic eruptions). Geoscience studies also include multidisciplinary studies related to paleoclimate research (see *Climate and Paleoclimate*). Process studies in modern arctic lakes are needed to understand how ancient lake sediments and enclosed fossils record changes in local and regional climate. Despite years of research and mapping by both academics and the U.S. Geological Survey, many aspects of arctic geology are only understood at a reconnaissance level. Major questions remain unanswered in large part due to the expense of access to remote regions. Specific recommendations for arctic geoscience research are outlined in a 1991 report of the National Research Council (1991), but few of these recommendations have been implemented due to serious logistical needs. For example,

- Carefully selected, detailed studies could answer many questions concerning the pre-Mesozoic paleogeography of Arctic Alaska and its relationship to ancient western North America, the evolution of the Brooks Range, and the Arctic Basin.
- Studies of the evolution of the Brooks Range and the basin to its north should be emphasized because this has a direct bearing on the North Slope petroleum province. This area contains the two largest oil fields in North America and has the best onshore potential for future hydrocarbon discoveries.
- Studies of the western Brooks Range offer significant potential for the discovery of additional mineral resources (*e.g.,* Red Dog zinc-lead-silver deposit and extensive coal deposits).
- The tectonic evolution of the Arctic Basin needs to be better understood. This evolution is intimately linked with crustal spreading centers that come ashore in Siberia via the Laptev Sea, yet scientists can only speculate as to how this system affected arctic terrains and the opening of the Arctic Basin.

- The tectonic suturing of parts of the Arctic, but especially Alaska, makes the Alaskan region a perfect laboratory for understanding the nature of large thrust earthquakes, such as those predicted to strike the Pacific Northwest in the future. Information needs to be gathered about the accelerations and source processes of earthquakes in southern Alaska and the Aleutians. These data will help scientists to make knowledgeable recommendations about other areas, such as the Pacific Northwest, in order to minimize the effects of the next large earthquake in such regions.

Research that Crosses and Integrates Domains

This section includes three research areas (social sciences, including health research, contaminant studies, and marine wildlife biology) that ask questions about, and require logistics for, more than a single domain. For example, depending on the question they are asking, marine mammal researchers may need access to sea ice, open ocean, or land. Because of their diverse science questions and logistics needs, these research areas can link other, more disparate disciplines leading to mature syntheses that combine the social sciences with the biological and physical sciences. These syntheses will require scientists from different disciplines working together in the field to provide strong knowledge bases for solving issues important to humankind.

Social Sciences

The history of social science research in the Arctic has been closely tied with the history of European expansion and exploration into the region. Virtually every traveler who kept a journal recorded observations about the peoples who dwell on the tundra. Many explorers such as Amundsen, Nansen, Rasmussen, and Steffansson imitated the clothes and travel methods of the Inuit and other peoples. Those who did not frequently perished. The physical difficulties and costs, however, limited intentional and systematic research in the Arctic to a few notable expeditions.

Social scientists benefited tremendously from the post-World War II development of air transportation in North America and roads in Fennoscandia, coincident with the concentration of formerly dispersed populations into larger communities. These developments were also associated with the expansion of social services, large-scale resource extraction, military facilities, and government management of resources. Thus, improved physical access has brought with it substantial social change.

Social science research is now focusing on the interaction among environmental, economic, and social change. The role of human-induced changes in global environmental change in the Arctic is far less well known and were assumed to be relatively minor until contaminants were found in the Arctic Basin. The origin of these contaminants is still unknown; some evidence points to industrial and military activity in the North. Large-scale landscape changes, such as dam construction, forestry, and fires caused by humans, may be driven by combinations of world market forces, local economic aspirations, and national policies. The interface between human residents of the Arctic and resources such as caribou, waterfowl, marine mammals, and anadromous fish has not been thoroughly examined in light of changes in the distribution and dynamics of indigenous people of the Arctic and the dynamics of the animal populations. Factors critical to the sustainability of human communities in the Arctic need to be examined. Knowledge of the effects of industrial and subsistence activities is a central contribution of the social sciences to global change studies. This "cultural ecology" approach to social science requires some long-term monitoring of environmental variables and therefore some novel logistics capabilities. More details about this approach of social science to work in the Arctic can be found in the *People and the Arctic: A Prospectus for Research on the Human Dimensions of the Arctic System* (ARCUS, 1997).

Conversely, the traditional communities of the Arctic face a range of forces that originate outside their regions. These have included in the past direct efforts at socioeconomic and cultural change, but more recently indirect effects from linking to world markets and media, industrial development, contaminants, and anthropogenic climate change. Understanding the impacts of these changes requires differentiating actual change from demographic differences in life cycles or populations (longitudinal studies) and the effects that cultural, national, and other geographic differences may have (comparative studies).

Most studies investigating the effect of extra-arctic forces on traditional communities concern such questions as individual and community resilience, adjustment, and survival (National Research Council, 1989), health, economic alternatives, linguistic change, and natural resource regimes. These studies require the development of long-term relationships that entail frequent, often extended, visits over long periods of time. Students need to be trained and supervised, not just in the actual conduct of research, but also in relations with communities, and the need to include people from these communities in research teams as students and in other positions whenever possible.

Historical and archaeological studies contribute to our understanding of the response of the traditional cultures of the North to spatial and temporal variations in resources (often as a function of shorter or longer term climate change). This understanding includes the development of political systems for controlling and distributing those resources, and the development of social infrastructure for modifying subsistence systems as available resources vary over time. Such research has been particularly difficult to carry out in the Arctic because of the need to cover large numbers of small sites. Regional archaeological surveys are essential for defining the universe of sites and therefore for valid sampling. They are also necessary for research projects addressing larger-scale issues.

Prehistoric kitchen revealed at Pingusugruk, Point Franklin, Alaska (photograph by Glenn Sheehan).

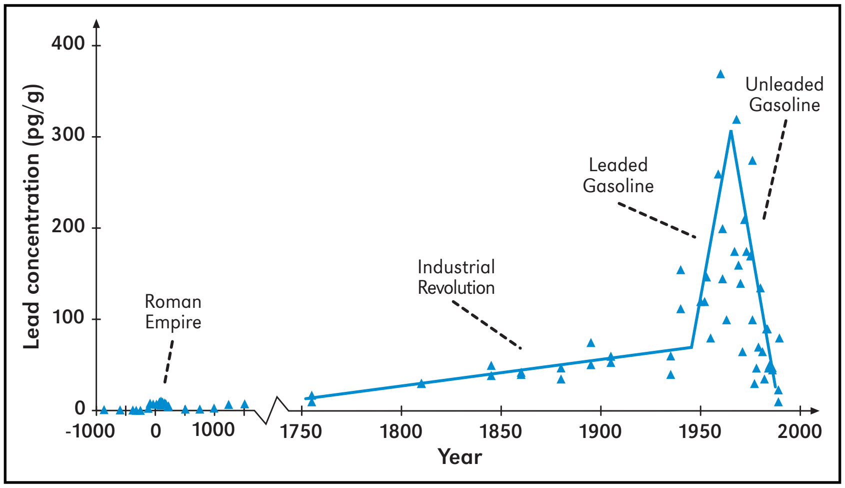
Despite major advances in improving health care in northern communities, several major health problems continue. Diseases thought to have been defeated are reappearing, *e.g.,* tuberculosis. "Lifestyle diseases," due to smoking, overconsumption of alcohol, and replacement of traditional foods with imported processed foods of low nutritional value affect arctic populations at higher-than-average rates. Poor sanitary conditions contribute to the persistence of medical conditions effectively addressed elsewhere in the U.S., such as infant diarrhea and dehydration. Finally, significant levels of contaminants are appearing in important arctic food resources. Health research also requires an added dimension focusing upon the impacts of the human-made environment upon arctic residents and arctic visitors. For instance, no baseline studies have been performed to establish the effects upon indoor air quality of the super-insulation often required to maintain livable temperatures during winter. Key research issues to be addressed include:

- feedbacks between processes, both physical and biological, and human activities on global and regional scales;
- records of disappearing archaeological sites and cultural/linguistic traditions;
- differential effects of commercial, industrial, and military activities in the Arctic;
- factors affecting arctic community and individual resilience under resource variability through space and time;
- current health and nutritional status of arctic residents and visitors, and the ways in which they can be improved;
- importance of traditional and contemporary community knowledge to environmental research and resource management;
- causes, nature, and impacts of rapid social and cultural change in traditional societies;
- role of education in maintaining culture and adapting to the future; and
- sustainable futures for arctic communities.

Contaminant Studies

The concentrations of contaminants in food chains are of increasing concern to arctic inhabitants. Evidence of a broad range of contaminants has been found in the Arctic, including organic pesticides, heavy metals, radionuclides, and PCBs. Models of risk assessment used elsewhere in the world cannot be readily applied because processes of transport, contaminant cycling, and biological exposure are unique to the Arctic.

Contaminants not originating in the Arctic are transported into the region by the atmosphere, ocean, and rivers. Aerosols and volatile chemicals originating in temperate or even tropical locations are carried northward during winter by prevailing winds to the Arctic where they are trapped in the cold atmosphere until they precipitate or condense to arctic surfaces. Inflow



Lead data from Greenland snow showing the global impact of human activities and effects of clean-up (figure modified by Richard Alley).

of Atlantic water through the Fram Strait and Pacific water through Bering Strait provide routes of ocean transport of contaminants to surface and near-surface waters in the Arctic Ocean. Most arctic rivers flow north, draining large watersheds and carrying agricultural, industrial, and radionuclide pollutants. Contaminants entering the Arctic are redistributed by winds, ocean currents, and sea ice.

Arctic biological processes cause the food web to be unusually susceptible to contaminants. Species are vulnerable to disruption because diversity is low. The higher trophic levels of the food chain are dependent on fat which greatly enhances biomagnification. The longevity of some species combined with high levels of biomagnification results in a marked accumulation of contaminants. Finally, the dependence of many arctic peoples on subsistence living increases the likelihood that contaminants will be ingested.

The understanding of the movement and fate of contaminants is inherently related to understanding physical and biological pathways, and contaminant cycling processes. Models of contaminant transport, chemical processes, and food chain transfer need to be developed for marine and terrestrial systems. In addition, sensitive indicators of ecosystem health (the canary in the mine) need to be developed. Important research issues include:

- long-term baseline data on levels of contaminants in the environment to elucidate current burdens and spatial and temporal trends. Sampling should include atmosphere, ocean, ice, snow, rivers, sediments and terrain.
- contaminant incorporation and cycling in atmosphere, ice, ocean and sediments;
- contaminant transfer and distribution through all trophic levels;
- biotic indicators of ecological and ecosystem health; and
- baseline data on contaminants in marine mammals needs to be extended back in time through the use of biological specimens from frozen archaelogical sites (*e.g.,* blubber and muktuk from kitchens and caches can date to at least 800-1,000 years BP).

Marine Wildlife Biology

The seasonally ice-covered waters of the Bering, Chukchi, and Beaufort Seas are home to eight species of pinnipeds, 16 species of cetaceans, as well as polar bears and arctic foxes. There are ca. 230 species of birds that visit the Arctic, ca. 150 of which breed in the Arctic; 70–80% of the total are aquatic or coastal species. Pinniped diversity is greatest in the polar regions contrary to the usual biogeographical trend in species richness. The wealth of marine animals in northern waters has been vital to indigenous people both in the past and at present. Walruses, for example, are estimated to have an equivalent cash value of several million dollars per year to the Native peoples of Alaska. Over the past 150 years, the Pacific walrus population has been over-harvested repeatedly. Each time the population has started to recover, it has been subjected again to excessive harvests in large part due to a lack of timely data and inadequate coordination between U.S. and Russian managers. The investigation of walrus ecology has all but ceased with no adequately ice-strengthened vessels available in the U.S. or Russia; between 1975 and 1990 censuses of the Pacific walrus were conducted jointly by the U.S. and Russia every five years, but none have been carried out since 1990, and none are planned due to a lack of aircraft support in either country.

Additional data are needed on the bowhead whale and its international travels in the Bering, Chukchi, and Beaufort seas, in light of its endangered status, the potential impacts associated with shipping and offshore oil and gas activities, and its cultural and subsistence importance to the Native peoples of Alaska, Russia, and Canada. In the last two decades, fur seals, harbor seals, Steller sea lions, and some marine bird species have declined dramatically in the Gulf of Alaska and the Bering Sea. The cause of those declines is not known conclusively, but many researchers suspect a decline in populations of fish preyed on by pinnipeds and sea birds. Spotted and ribbon seals also depend on fish in the Bering and Chukchi seas, but neither species is the subject of significant investigation in the United States, largely due to the lack of logistic support adequate for studying species that live much of the year in the pack ice. Important scientific issues in marine wildlife biology include:

- The importance of the spring lead system as part of the migration corridor for walrus, bowhead whales, beluga whales, eider ducks, and other marine mammal and bird species. Before the ice breaks up in the spring, migrating animals are concentrated in the lead system, making them potentially vulnerable to increased ship traffic through the Bering and Chukchi seas; shipping may increase with development in the Beaufort Sea, Arctic National Wildlife Refuge, National Petroleum Reserve, or of an arctic shipping route to Europe.
- Investigations of the leading hypotheses of the cause of the population declines in the Bering Sea and Gulf of Alaska.
- Comparisons of the genetic makeup of summer bowhead whale groups in the Chukchi and Beaufort seas and of bowhead whales found at arctic archaeological sites. Potential differences between current groups have recently been identified; little historical data is available. These animals are important cultural and subsistence resources.
- Sex and age composition information on walrus herds that summer in the Chukchi Sea is needed to estimate productivity, survivorship, and recruitment. Current information comes from the subsistence harvest or aerial surveys, neither of which provides sufficiently detailed or accurate data. These animals are important subsistence resources for Native people in Alaska and Russia.
- Information on bowhead whales' reproduction, feeding, contaminant burdens, interactions with offshore industrial activity, and movements between U.S. and Russian waters.

Information on sex and age composition of walrus herds that summer in the Chukchi Sea is needed to estimate productivity, survivorship, and recruitment (photograph by Lori Quakenbush).

Logistical Requirements

Recommendations for a logistics infrastructure to support the arctic science discussed in Chapter 2, *Science Questions*, are outlined here in similar categories. For the most part, the logistics recommended here are at present technologically feasible. In some cases, continued enhancements of technology to provide improved logistics are advocated. In other cases, the logistical resources are not currently available or the support structure is not suited for providing those logistics. These requirements were developed from a community workshop, surveys, and subsequent discussions.

Atmosphere

The highest priority research requires the creation of permanent facilities, continued development of existing facilities, deployment of mobile and autonomous remote sensors, and the creation of a system of multiple-use platforms to allow access to the arctic atmosphere and surface by a wide variety of investigators who have specialized instrumentation and equipment to make the necessary measurements. The surface in the Arctic is highly variable, and no single means of access can accomplish all the tasks that are needed. The Arctic consists of ice sheets, snow-covered and open tundra, boreal forests, sea ice, open ocean, mountainous terrain, and fresh-water lakes. For the purpose of understanding the arctic atmosphere/climate system, all of these surface types must be accessible. Linkages among atmosphere, wildlife, and human interactions require measurement of climate variables within regions. Existing data series do not adequately reflect important differences between coastal and inland conditions. In addition to the surface, routine access to the atmosphere itself is necessary. In particular, measurements of the physical, chemical, and radiative properties of arctic clouds are a high priority as these cloud systems are the primary regulators of the flux of solar and terrestrial energy through the atmosphere that will ultimately determine climate trends in this region. In spite of this, very little is known about arctic clouds and how they regulate the climate of the Arctic. Long-term measurements of atmospheric properties such as chemistry can be accomplished from existing ground stations such as the NOAA CMDL station at Barrow. Because the arctic atmosphere is stratified much of the year, measurements made at sea level (such as Barrow) do not necessarily reflect the conditions found at higher altitudes. Although aircraft can be used for this purpose, they are not well suited to make measurements over the long term. A high elevation site could be used to conduct studies of the composition of the middle atmosphere, the processes involved in atmosphere/ice interactions, and the recording of the atmospheric composition and climate in glacial ice. Finally, the upper atmosphere environment including the stratosphere, ionosphere, and magnetosphere can be studied from the ground by remote sensors and satellites. These measurements will provide new information on the solar wind and its effect on a variety of magnetospheric and ionospheric processes. Logistics required to meet the science needs are:

- support a long-term observational site at Barrow, including ground-based remote sensing, to measure clouds, atmospheric radiation, atmospheric vertical structure, surface fluxes of heat and trace gases, and atmospheric chemistry (including aerosols);
- support long-term monitoring of atmospheric vertical structure, cloud properties, surface heat-fluxes, precipitation, and ice characteristics at a site in the Arctic Ocean;
- develop the capability to augment the surface pressure buoy network with measurements of air temperature, winds, radiation, and possibly precipitation and column water vapor path;
- maintain capability and support for conducting short-term process studies that involve the use of research aircraft and ice camps;
- continue international collaborative support of the developing Polar Cap Observatory at Resolute, NWT, Canada, with its focus on upper atmospheric, ionospheric/magnetospheric measurements, and geospace environment;
- develop a high elevation sampling site (Summit, Greenland) for atmospheric and atmosphere/ice interaction measurements;
- provide access to a wide range of arctic environments by establishing transportation capability (aircraft) for remote sensing investigations, camps, and remote autonomous station deployment;
- create specialized instrument and remote sensing deployment capability utilizing icebreakers, submarines, aircraft, remotely piloted aircraft, blimps, and tethered balloons; and
- increase numbers of remote site recording stations for pressure, temperature, precipitation, and wind conditions in major study regions.

Ocean/Sea Ice/Seafloor

Ocean Circulation

Sea ice, the overriding marine navigational concern in the polar regions, presents a more formidable obstacle in the Arctic than in the Antarctic, because of its largely multiyear structure and its generally thicker and more permanent nature. Arctic Ocean ice is therefore less saline, stronger and more massive, and accordingly imposes more severe requirements on icebreaker technology. A strong ship with superior maneuverability, minimum resistance in ice, and long endurance is required. Practical and safe arctic oceanography will sometimes require two-ship operations, which have been found to be prudent and effective in recent arctic transits.

To address the scientific issues outlined in Chapter 2, *Science Questions, Ocean/Sea Ice/Seafloor*, a variety of logistical means must be used, each of which is most useful in a particular season and at specific sites. Surface ships are used in the summer when there is less sea ice, or they are confined to the marginal seas. Aircraft surveys and short-term ice camps are used in the spring when the sea-ice cover is solid, and there is daylight for aircraft operations. Automated instrument platforms have made it possible to carry out basin-wide observations over all seasons. The

International Arctic Buoy Program has been air-dropping buoys over the entire Arctic Ocean. These measure atmospheric pressure and temperature and track the motion of the sea ice and report the gathered data through a satellite link. Other more complicated buoys measure upper ocean and sea-ice characteristics as they drift with the ice. The real-time data from these automated platforms have been used in improving weather prediction, learning the statistics of ice motion, validating numerical models, and providing ground truth for remote sensing observations. Autonomous Underwater Vehicles (AUV) offer the possibility of rapidly making spatial surveys of a variety of water, biological, and ice properties beneath sea ice. These operate without intervention from the surface and have the potential for navigating considerable distances [1 to 100s km]. Several of these vehicles have been used in the Arctic Ocean, and they are becoming increasingly effective. Remotely Operated Vehicles (ROV) which are controlled from the surface through a tether (typically 100 m range) are opening the under-ice environment to close examination and sampling to a degree previously available only to divers. Specific logistical needs include:

- ❖ Access to the Arctic Ocean during spring, summer, fall, and winter to study the temporal variability of physical processes in the ocean, ice, and atmosphere using a variety of occupied and autonomous platforms (combined use of icebreakers, submarines, aircraft, and ice camps is required to achieve adequate spatial and temporal resolution).
- ❖ Aircraft support for hydrographic surveys to monitor the changes in the hydrography and circulation of the Arctic Ocean. Such surveys would keep the time series started by Russian investigators intact.
- ❖ Support for near-shore studies with shallow-draft, ice-strengthened vessels, aircraft support, and temporary ice- or shore-based camps. This includes a vessel replacing the *Alpha Helix.*
- ❖ Continued development of autonomous platforms for continuous sampling and AUVs and ROVs for specific surveys. These are probably the only means to increase the temporal and spatial coverage of our measurements to the scientifically required level.
- ❖ Routine information and coordination for scheduling of available platforms with emphasis on use for cross-disciplinary efforts.
- ❖ Access to foreign territorial waters, such as Canada and Russia, for sampling to address major science objectives. Specifically, negotiations at the appropriate political levels should be initiated to achieve good access to the Russian Arctic.

Sea Ice

The major priority for sea-ice investigations is access to the ice throughout the year. The heat exchange is least understood for the summer when surface conditions of the ice cover are most variable. Investigations of the properties and processes need to be carried out during the summer to adequately model the energy balance. Energy exchange processes are more straightforward during winter when solar radiation is not a factor, but accurate modeling requires detailed knowledge of the amount of thin ice and open water. It is likely that most sediment and contaminant incorporation also occurs in fall and winter in the ice production areas on the shallow shelves. These shelves are also recipients of the dense brines that have resulted from the growing ice. Biological processes begin when light begins to penetrate the ice and water column and continue until the fall. The needs identified to conduct detailed investigations of these processes are:

- periodic, year-round ice-ocean-atmosphere process studies from ice camps or drifting platforms;
- shore-based staging facilities for near-shore process studies with aircraft support for offshore investigations and autonomous sensor deployment;
- regular icebreaker access to the shelves and central Arctic during spring, summer, and fall;
- continued support of development and deployment of autonomous instrumentation to monitor ice-mass balance, mechanical properties, and chemical properties;
- development of specialized drifting buoys for the shelf regions that may be exposed to freeze-thaw cycles;
- regular seasonal surveys of ice thickness (including ice bottomside swathmapping) at selected locations by submarines, AUVs, or ROVs;
- use of submarines to service and deploy autonomous platforms; and
- spring, summer, and fall monitoring of ice-surface characteristics at selected locations with small aircraft or remotely piloted vehicles.

Seafloor

The fundamental basis of understanding the tectonic history and evolution of the arctic region lies in determining the geologic framework and the tectonic history of the Arctic Ocean bathymetric complex, especially that of the more inaccessible Amerasian Basin. While there is some consensus concerning the rift origins of the more accessible Eurasian Basin, divergent hypotheses exist concerning the western Arctic. The needs identified by the National Research Council (1991) to test these hypotheses include:

- Establish a standard network of modern digital seismograph stations entirely around the circumarctic rim. This will require international collaboration on deployment of electronically accessible instruments and necessary field visits
- Use submarines or aircraft for regional magnetic and gravity mapping of the entire Arctic Basin.
- Use submarines for seabed, side-scan sonar imaging, bathymetric mapping, and seismic reflection and refraction studies of the entire Arctic Basin.
- Sedimentation studies require samples from shallow cores (piston, gravity, box), high-resolution seismic reflection profiles, and continental shelf drilling.
- Gas hydrate studies require multichannel seismic reflection and refraction data and samples from cores or shallow drill holes on outer continental shelves or upper slopes in seasonally sea-ice free or light sea-ice areas.
- Paleobiogeographic and paleoecologic research require samples from drill holes on the continental shelves. This work involves access to ice-stengthened drill ships for the collection of sediment/rock cores.

- Ice-rafted sediment studies require satellite imagery and samples from sea-ice and shallow sub-seabed cores. This requires shallow draft vessels for seabed sampling within the loose pack ice.
- Geophysical studies along continental margin transects and later coring, drilling, and study of the sea-level record and paleoclimate record of the region require use of an ice-strengthened ship for accessing arctic shelf areas as sea ice permits and use of a drill-ship.

Biogeochemistry

Emphasis in biogeochemical investigations should be placed on the seasonal cycles and long-term climate related variations. Most studies have taken place in summer and in the marginal seas, for which accessibility has not been a major problem. Future studies are necessary in the central Arctic which has recently been shown to have an active biological community. More efforts at quantification of the primary production and the carbon cycle are necessary. Studies of biogeochemical processes on the shelves and slopes and, particularly, exchanges with the basins are of primary importance. Recommendations for logistics to address biogeochemical investigations are:

- access to year-round drifting ice stations for temporal investigations;
- year-round icebreaker access to the arctic shelves for spatial sampling of water column and benthos;
- multiplatform investigations for outer shelves and slopes (drift stations, icebreaker, ice-strengthened ship, helicopter);
- access to Russian waters for shelf-basin studies;
- increased use of submarines for biogeochemical investigations which will require enhancement of laboratory space and increased berth space for scientists; and
- establishment of facilities and support for long time-series measurements of key chemical and biological parameters.

Ice Sheets and Glaciers

Determining the reproducibility of the paleoclimatic records and examining for other possible indicators will require additional ice cores from Greenland and the circumarctic. Detailed studies of the dynamics of ice sheets are necessary to understand mass balance, ice-atmosphere, ice-ocean, and ice-sediment interaction. The basic logistics problem facing ice-sheet research is continued access to ice sheets where study sites are most often in remote, difficult to access locations. Conducting field surveys, coring, and returning samples requires optimizing available transportation resources and continued technological improvements for lightweight equipment and automatic monitoring instrumentation.

Chapter 3

Logistical Requirements

High-Resolution Paleoclimatic Records from Ice Cores in Greenland and the Circumarctic

Advancement of ice-core research requires developing better circumarctic coverage including high-altitude, Russian, Greenlandic, Alaskan, and Canadian sites (some detailed in the Ice-Core Circum-Arctic Paleoclimate Program [ICAPP] project report, and in reports of the U.S. Ice Core Working Group) and providing additional coverage of important sites and times so that measurements can be conducted that now are limited by lack of core samples. Specific logistical requirements for continued ice-core research include:

- maintain access to remote-sensing data from other agencies to allow optimization of field programs;
- develop diverted-drilling or side-wall-coring capability or other technology for the collection of larger sample sizes at key depths required for studies of constituents in low concentrations;
- explore new technologies for rapid access to deeper, older ice for resolution of the paleoclimatic record, including use of different drilling technologies at different levels in one hole, and use of surface-launched melter probes;
- improve lightweight drilling technology for shallow and intermediate depths;
- provide helicopter and fixed-wing aircraft support for high-altitude, high-payload operations; and
- maintain continued access to drill holes and sites for borehole logging, strain measurement, dynamics, and atmosphere-ice interaction studies.

Continued ice-core research requires improved lightweight drilling technology for shallow and intermediate depths (photograph by Richard Alley).

Ice-Sheet Dynamics

The ice-sheet dynamics investigations include mass balance, studies of surging glaciers, sedimentation, transport, dynamics, and hydrology. In Greenland, access to the surface is required to document atmospheric, surface-snow, and ice-flow conditions. The range of questions on the behavior of ice masses dictates a wide range of scientific strategies, and of associated logistical strategies. Investigations include satellite monitoring, airborne geophysics including radar sounding, laser altimetry, gravity and magnetics, typically from small planes, surface surveys mounted on foot or from snowmobiles and supported by helicopter or light plane, shallow ice coring, hot-water access drilling to the bed, automatic weather stations, proglacial stream monitoring, calving and grounding-line studies from boats and remotely operated submersibles, and more. Logistical requirements include:

- improve hot-water and auger capability to provide access holes for glacier and glacier-bed studies and seismic shooting;

- provide helicopter and fixed-wing aircraft support to remote study sites on arctic glaciers;
- develop and enhance long-term autonomous monitoring instrumentation; and
- expand availability of surface and airborne traverse equipment for studies of weather conditions, glacier motion, subglacial water pressure, etc.

Terrestrial Science

Arctic terrestrial sciences require logistics ranging from large field stations to transect sampling with a helicopter. Flexibility and adaptability in terrestrial science logistics are crucial as different science needs and locations develop. Permanent field laboratories permit the study of natural processes in detail and the accumulation of long-term measurements. Existing towns and villages already provide significant logistical support for arctic research; their usefulness, both as sites for research and transportation nodes, could be greatly increased by modest investments in assets such as secure storage facilities. Mobile field camps can facilitate work over a wide area or studies by a single project at a site for one or several years. Finally, arctic terrestrial research also needs some special facilities or special equipment; these can be shared among several projects. For example, drilling rigs are needed to collect cores from permafrost and lake sediments. A network of instrumented permafrost wells needs to be set up.

Existing towns and villages already provide significant logistical support for arctic research. Here, local residents in Kotzebue, Alaska prepare to transport field gear to a distant campsite where geologists plan to work on the glacial and sea level stratigraphy of Baldwin Peninsula (photograph by Julie Brigham-Grette).

Access to Russian field stations and field sites is a difficult and important issue. The current view is that the complex and volatile bureaucratic requirements are so daunting that little research is proposed. Clearly, access to permanent facilities is needed at a minimum of two sites across the Russian Arctic; while the political and economic system of Russia is in flux, however, it may be most practical in the immediate future to use mobile facilities for greater flexibility.

Permanent Field Laboratories

Additional permanent laboratories are needed at sites around the Arctic where intensive and long-term studies may be carried out. Each of these must be capable of providing full support of living and scientific needs of 40 to 50 scientists. At the present time, there is one fully developed inland laboratory at Abisko in northern Sweden, one laboratory at Kangerlussuaq in western Greenland, one at Zackenberg in northeastern Greenland, two on Svalbard, and one inland laboratory in Alaska at Toolik Lake; there are no federally supported laboratories on the Alaskan coast. Barrow would appear to be a logical choice for an Alaska coastal facility with its existing infrastructure and associated science activities (ARM, BASC, BEO). Present and future U.S. laboratories should be supported primarily by direct grants from the government to allow long-term planning by scientists and facilities managers. Each of these permanent laboratories would provide helicopter support each summer and logistics support as needed to associated field stations and temporary camps.

Permanent laboratories fill the logistics needs of many types of terrestrial research, including long-term monitoring of climate, plant species and community change, invertebrate and vertebrate animal distribution, and geomorphology studies of rivers and coastlines. Detailed studies of the physical system, including hydrology, permafrost, and the active layer, are aimed at modeling the present and future conditions. Permanent laboratories are also logical for field studies of animal and plant physiology, work on the microphysics of arctic clouds, and studies of UVB effects. Finally, multidisciplinary and experimental measures of ecosystem processes and fluxes of materials, such as the Long Term Ecological Research project (LTER) and ARCSS/LAII, require the database and facilities of a large, permanent field station to address questions such as the microbial controls on decomposition and trace gas production and the effect of species change on communities in lakes.

Mobile Field Camps and Transportation Nodes

Mobile field camps frequently are necessary for biological and geological sampling over wide areas. Oil exploration companies working in the Arctic have developed a flexible approach to their logistics needs that can be adapted for research. A set of modular camp buildings, mounted on trailer/sled runners, can be moved easily from location to location as the scientific demands change. The size and capacity of each camp could be changed by adding or removing buildings. This approach requires the careful design and construction of these robust and arctic-worthy mobile homes/labs, along with a plan for deployment, storage, and maintenance. With buildings outfitted with heaters and self-contained sewage and cooking systems, camp set-up would require only moving the building to a site. The buildings would serve equally well placed in or near a village or town, or in a remote location. Some mobile field camps could act as satellite field stations if left on a site for several seasons. The design should include considerations of moving the buildings over snow or on the road system, or transporting them by ship to Russia for a multiyear campaign.

Small portable field laboratory units are needed for use in large mammal studies—one should be transportable via helicopter, over snow sled, and in large aircraft; the other should be a trailer-type unit moveable over the Dalton Highway and connecting road system. The improved access provided by such portable units would also allow studies of the controls of snow distribution and monitoring studies of modern climate variability over 5 to 10 years along east-west and north-south transects.

Mobile stations would allow the testing of the ARCSS LAII flux measurements of trace gases in new plant community types, such as the shrub tundra of western Alaska. The experiments carried out at permanent labs on the effects of nutrients and grazers on streams and lakes (LTER) and the effect of small-plot heating on plant communities (International Tundra Experiment [ITEX]) could be expanded to a wider area by the use of satellite stations.

Both permanent and mobile labs would be suitable for studies of the behavior of unconfined large mammals using GPS signals from instrumented caribou and muskoxen. Large mammal research on instrumented but tame caribou and muskoxen could also be done at both sites if transport and holding facilities were available. Mobile camps located in wetlands of importance for waterfowl and shorebird nesting would be valuable for comparative ecological studies of arctic nesting birds. Suitably located mobile labs, for instance on the northwest coast of Alaska, would also facilitate marine mammal research (see this chapter, *Integrative, Cross-Domain Research, Marine Wildlife Biology*).

Each field camp could be serviced (communication, transportation via commercial small planes or helicopters) as needed from a transportation node. In some cases, permanent laboratories may act as nodes. Established villages on national airline networks are already used by researchers as logistics hubs. Modest and flexible additions to their existing facilities would greatly improve their usefulness to investigators; these additions would include an as-needed coordinator, access to radio communication (especially for arranging emergency medical evacuations), and storage facilities. The node coordinator could also assist with arranging with researchers from federal agencies the shared use of helicopters, fixed-wing flights, and boats. In Russia, facilitators are also needed to assist with local politics, the processing of local permits, and access to special science bank accounts for payment of local logistical hires. Moreover, at present there is no way to get necessary field gear into and out of northeast Russia without chartering a small plane; excess baggage on Alaska Airlines into Magadan, Khabarovsk, or Vladivostok is carried on a space-available basis only.

Storage is needed for field gear (tents, small boats/zodiacs, fuel) required from one season to the next. Many government agencies in Alaska, for example the National Park Service, Fish & Wildlife, or the U.S. Geological Survey, have storage facilities, as well as temporary bunkhouse accommodations in Nome, Kotzebue, and Kaktovik, but these agencies are not currently obligated to allow researchers to use the storage space or to provide overnight accommodations for researchers in transit to field locations. Formal agreements or memoranda of understanding could be established, perhaps implemented via a node coordinator or facilitator, so that cheap storage and short-term accommodations can be made available. In communities where significant numbers of researchers are based each season, such as Prudhoe Bay and Barrow, dedicated secure storage facilities for investigators are needed.

Facilitation of permitting required by local, state and federal agencies for access to specific areas and for sampling is required. In addition to Alaska, this should include facilitators in Greenland, Russia, and Canada to assist with permits and local politics.

Integrative, Cross-Domain Research

Social Science

The logistical needs of social scientists are diverse, and many are relevant to any scientist working in the Arctic. Many social scientists work within communities that can be reached by regular air service. In many places board and lodging are not available commercially, but alternatives include private homes, schools, and vacant dwellings. Usually some place is available for researchers who are adept at making connections. This picture differs substantially for archaeologists whose needs more closely parallel the physical and biological sciences. They must get to remote areas and bring their equipment, team, and living conditions with them. Health studies are a unique area with special logistical needs because of biohazards. For these reasons, this section is divided into three sections: social sciences in general, archaeology, and health.

General Social Science Needs

Working with local communities throughout the Arctic is a major part of social science. Current NSF guidelines for the conduct of research in the Arctic require close working relationships with indigenous peoples. Scientists of all disciplines need to be able to interact with arctic communities throughout the research process. This may include soliciting community priorities for research, collaborating with communities on research designs, involving communities in the research itself, and discussing the implications of research results with communities. Points of contact for coordination, such as the Alaska Native Science Commission, may aid researchers in coordinating work with communities. These coordination points of contact can be voluntary. Services could range from advising on needed research, to identifying community leaders, to help in setting up community education programs. In some regions, for example Canada and Greenland, researchers must seek permission for their research through local coordinating bodies.

Maintaining community relations generally requires frequent travel over long periods of time to build and maintain contacts. This is true of individual research projects as well as in the longer term development of multiproject programs. Education, including discussing planned research with local communities and reporting to them on research results, is also an important part of such projects. Support for local students to work with researchers needs to be recognized as a legitimate cost. Project costs need to include funding for a number of activities not necessarily directly related to research such as travel for pre-project planning, education, and other community interactions.

Of particular importance is the need to improve the means of communication into and from communities. While telephone systems exist in many areas of the North, they are subject to frequent breakdown. Full use of existing satellite systems would provide alternatives. For example, access to the University of Alaska e-mail system could substantially improve communication in the regional centers. Use of these systems would also support alternative ways in which to return research results to communities. Global satellite telephone communication would substantially improve safety and communication in many areas of the Arctic. This logistic improvement would benefit all researchers working in the Arctic.

Social scientists often work year-round; they need a basic understanding of survival skills and risk reduction. Survival training and preparation should include use of traditional knowledge when appropriate.

Social scientists would benefit from cheaper alternatives to hotels in regional centers. Hotels can be unduly expensive for people spending several days, weeks, or months in one community or region, particularly during the tourist season. In some regional centers, lodging could be provided through low-cost camps similar to those used by construction companies, with some services such as e-mail, photocopying, and faxing provided. These broad logistics improvements should be extended to all researchers, including social scientists:

- Central points of contact, such as those that already exist in northern Canada and Greenland as part of the permitting process. Their development in other circumarctic areas, on a voluntary basis, would aid social scientists' access to northern communities and vice versa.
- Funding for travel not directly associated with actual research, such as for education and meetings to plan research, to develop effective research relationships with communities.
- Access to global satellite telephone communication (INMARSAT). Better communications will improve safety, logistical coordination, data protection, and education.
- Training in survival skills and risk reduction, including the use of traditional knowledge as appropriate. Such training should substantially reduce the risks for scientists—social scientists, in particular—who work year-round and frequently rely on ground transportation.
- Low-cost lodging, preferably in association with services such as e-mail, photocopiers, and fax machines, would help reduce the costs of long-term research in northern communities and reduce the hidden burden on northern communities of hosting researchers.

Archaeology

Archaeological research requires two types of logistics: single site and broader survey. The first moves a large group to a single site for the summer and has been the standard for much recent research. Future research would, however, benefit from greater mobility during a single field season, addressing the need to look at a number of sites, some of them small, over a much larger region. Two possibilities exist for achieving this mobility: in areas with good coastal access—an ice-free season and relatively deep water near shore—a boat capable of holding a small crew and moving in relatively difficult waters could provide both mobility and a base camp. In all areas, helicopter or fixed-wing planes would be needed to move crews periodically between sites. This method was used effectively during the construction of the Trans-Alaska Pipeline. Periodic transportation is also needed even for established field camps.

Archaeologists need regional gear depots for setting up field sites. These depots could provide tents and other camp gear. Their location would depend on a number of factors. In Alaska, for instance, a regional center in Anchorage would facilitate efficiency in distribution. Equipment located in regional centers, such as Barrow, Kotzebue, Nome, and Bethel, would, however, make it easier to fulfill emergency needs during the field season. Regional processing centers would allow space in which to work with local communities on material (identification, etc.) as well as the handling of artifacts for shipment. Such regional processing centers would also allow some preliminary studies of materials and provide the ability to alter research strategies during the field season. Needs identified to improve archaeological research include:

- Use of helicopter or fixed-wing planes to move research crews periodically between sites would allow archaeologists to pursue geographically extensive research questions.
- Regional depots would cut individual project costs. They could be coordinated with other disciplinary areas and possibly contribute to multidisciplinary research.
- Access to improved methods of communication for safety, such as INMARSAT, are necessary. Field camps are isolated and serious medical problems may arise.
- Regional material and data-processing centers would improve the ability to handle materials, improve community interactions, and would create greater research design flexibility.

Health

Health research has two important problems, adequate storage and transportation of samples, and transportation under strict biohazard control. Tissue samples need to be refrigerated and transported rapidly. At present, no consistent system exists for doing this. Biohazard handling means both special containers and training and emergency equipment for those handling the samples. Critical needs for health research include:

- adequate storage facilities and transportation of samples; and
- experts trained in handling and shipment of biohazards.

Contaminants

Identification of sources of contaminants and measurement of baseline levels are of major importance. Measurements of contaminants must consistently be made in conjunction with other field programs at terrestrial and ocean sites, with particular emphasis on long-term sites where contaminant cycling and incorporation may be studied. Sites for long term monitoring need to be established. Specific needs include:

- contaminant investigations included as part of other Arctic research programs;
- access to Russian terrestrial sites, rivers, and coastal shelves to sample contaminant levels and identify sources; and
- identification of and access to terrestrial and coastal sites for long-term process and monitoring studies.

Marine Wildlife Biology

The seas adjacent to Alaska support abundant and diverse populations of marine mammals, and provide one of the most favorable locations for marine mammal research in the world. Questions that can be addressed concern matters of intense interest to biologists, environmental managers, arctic residents, and state and federal policymakers. Problems and questions relate to topics such as population stability, interactions with fisheries, ecosystem health, physiological adaptations, and Native subsistence harvest.

Despite the importance of marine mammals to marine ecosystems, detailed investigations of arctic species have been limited, primarily by the difficulties of working in the marine arctic environment. A few dedicated biologists have made substantial contributions working in collaboration with Native hunters, who provided the logistic support, or with ship support provided by the U. S. Coast Guard and the National Oceanographic and Atmospheric Administration (NOAA), which has been valuable, but not available consistently. Scientific investigations of marine mammals in the Arctic presently are severely limited by a lack of logistic support. The principal needs are:

- ❖ research cruises on ice-breaking ships;
- ❖ the availability of ice-sturdy, small ship (200-foot-range) expeditionary support;
- ❖ aircraft support for aerial surveys and for establishing study sites on the ice;
- ❖ small boats, helicopter support, and small aircraft to provide access to animals on shore colonies and on sea ice; and
- ❖ shore-based field stations. Given the great expanse of marine mammal habitat in Alaska, three or four modestly equipped field stations appropriately located (*e.g.,* Nome, Pt. Hope, Barrow, and Prudhoe Bay) would be more valuable than a single large site. The stations ideally would provide affordable housing, research laboratories with freezer space, support shops, aircraft services, snow mobiles, small boats, fuel storage, and field equipment.

A researcher on the frozen Beaufort Sea near Prudhoe Bay radio-tracking a ringed seal hauled out in a subnivian lair. This work is part of a study to determine the number of lairs used by the seals and their locations. The lair, not visible from the surface, was originally located by the dog's keen sense of smell. The dog is now pulling a sled with survival gear and a shotgun for bear protection (photograph by Brendan Kelly).

Recommendations

The general recommendations presented here will require expansion of current U.S. arctic logistics support. This logistical function should be well coordinated at all levels, using existing resources whenever and wherever possible. The following five general recommendations are important to all major research areas. They represent, therefore, a broad community consensus for high-priority action. Recommendations for more specific disciplinary needs follow. Although they may not be as broadly based, most will have significant impact on the logistical capabilities of more than one research area, which are identified in each recommendation. The recommendations presented here reflect important science-driven needs, science that may be crucial to the broader advancement of knowledge. The five general recommendations critical to a coherent logistical support strategy for U.S. research are:

Ensure access to the Arctic over the entire year.

The U.S. Arctic remains one of the most difficult places on Earth to conduct year-round research, with many areas inaccessible in winter. Access to the Arctic requires a physical presence to perform certain studies and the ability to deploy instrumentation for measurement of specific parameters throughout the Arctic in any season. To secure this access, it is necessary to:

- make platforms available that can deploy personnel and instrumentation to land-based sites and the Arctic Ocean and adjacent seas year-round. Platforms that will extend research capability include capable icebreakers, aircraft support, winter housing at Toolik Field Station, and winter-over capability at the GISP2 Summit site.
- provide additional mobile base camps for short- and long-term studies on land, some of which would be available for winter use, including temporary but coordinated logistics support and laboratory space in Barrow, Alaska, and logistics depots elsewhere in the Arctic for the supply and mobilization of field camps.

Increase availability and use of remote and autonomous instruments.

All disciplines require some long-term observations in addition to intensive studies limited in space and time. Many long-term observations are currently provided by manned platforms, which should be replaced with remote and autonomous instrumentation as technology develops. To increase efficiency and comprehensiveness of data acquisition, it is necessary to:

- employ and encourage the development of a variety of remote and autonomous instrumentation systems, including Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), telemetry systems, moored water collection systems, deep floats, monitoring buoys, automatic weather stations, atmospheric samplers, borehole loggers, and remotely piloted aircraft.

- promote adaptation of existing technologies to extreme operating conditions. Increase the spatial and temporal resolution of long-term remote observations.

Protect the health and safety of people conducting research in the Arctic.

Improvements in health and safety will occur with the development of better access; safe and reliable transportation, adequate equipment, and good mobile field camps will remove the *ad hoc* and risky nature of some scientific efforts. Conversely, improved access will also increase the number of people in the field and thereby increase potential risks. The following measures are recommended to better protect the health and safety of researchers in the Arctic:

- Sponsor arctic travel skills and survival courses in cooperation with northern communities.
- Supply, as needed, portable telephone satellite communications, such as INMARSAT (the International Mobile Satellite Organization, the 80-member country inter-governmental organization, also owned by the private and public telephone companies of the respective countries, who market the INMARSAT space segment.)
- Identify a provider for cost-effective travel and health insurance to address health emergencies in the Arctic that can involve extraordinary expenses to investigators and federal agencies.
- Establish U.S. bank accounts in local Russian cities to help researchers avoid problems with cash and other means of payment in Russia.

Improve communication and collaboration between arctic peoples and the research community.

Arctic communities are keenly aware of the effects of science activities on their lives and are anxious to learn what science can offer to their understanding of the changes they are experiencing. Although many researchers have long recognized the value in working with local communities, relations with local communities cannot be taken for granted or ignored. This recommendation, as an issue of access and therefore logistics, cuts across disciplines because the location of a research camp in a traditional hunting area is as likely to concern communities as much as the presence of an anthropologist in the community itself. Scientists of all disciplines must be able to interact with arctic communities as appropriate throughout the research process. These interactions could include soliciting community priorities for research, collaborating with communities on research program design, involving communities in the research itself, and discussing the implications of research results with communities. Better physical access will aid relations with arctic communities. Good mobile field camps and year-

Scientists of all disciplines must be able to interact with arctic communities as appropriate throughout the research process (photograph by Kirby Sokiayak).

round research sites will, for instance, create places where local students can participate in educational programs. Still, researchers need assistance to improve cooperation with indigenous communities:

- make researchers working in the Arctic aware of the U.S. Interagency Arctic Research Policy Committee (IARPC) Guidelines for the Conduct of Research in the Arctic to enhance community/researcher relationships and access of investigators to research sites.
- help researchers establish communication with communities. Identify points of contact in each major arctic region for coordination with communities.
- formalize what has been *ad hoc* and *gratis* logistical assistance from local and regional authorities.
- extend the infrastructure that supports communication among scientists to support communication between scientists and communities. Most important is assistance with the establishment of telecommunications-links and on-site equipment that will enable communities to send and receive electronic mail, data files, and documents, and to access the Internet.
- seek guidance to accomplish these goals from trans-national native organizations, such as the Alaska Native Science Commission, the Inuit Circumpolar Conference and the Nordic Saami Council, by direct consultation and inviting them to participate in national and international meetings that address arctic science and logistical issues.

Seek interagency, international, and bilateral logistics arrangements to efficiently use all available resources and to reduce costs by avoiding duplication of efforts.

Much of what is needed to support arctic research is already present, but spread throughout federal agencies and among nations. Effective coordination will do much to address the logistical needs of the U.S. scientific community. Implementation of the previous recommendations, especially providing better access to the Arctic year-round, will substantially improve U.S. researchers' opportunities to collaborate and cooperate with international arctic scientists. Currently, such reciprocity is hampered by a lack of parallel U.S. logistical capabilities.

- make the IARPC logistical coordinating mechanism effective.
- fully implement the Arctic Logistics and Information Access and Services (ALIAS) Program.
- convene an international arctic logistics conference to improve communications and identify areas of common interest, and plan for potential collaboration.

Specific Disciplinary Recommendations

The five divisions used in organizing this document—(1) Atmosphere, (2) Ocean/Sea Ice/Seafloor, (3) Ice Sheets and Glaciers, (4) Terrestrial Research, and (5) Integrative, Cross-Domain Research—are referred to as disciplines for convenience, although they are largely not true academic disciplines but rather the physical domains where research is conducted. They arose by identification of common logistical needs within the divisions; the conceptual limitations of such artificial partitioning should be kept in mind. The numbers in blue in the following text correspond to the recommendations in the table on page 62-63. The table includes logistics recommendations, priorities, and timelines and provides a quick summary of the following information.

Atmosphere

1 Routine aircraft support for deployment of instrumentation and field study sites as well as studies of cloud properties, atmospheric structure and surface albedo. Use of small aircraft which could be based from the primary facility should be investigated.

2 Establishment of a permanent, primary facility to base a broad spectrum of field studies. A likely choice is Barrow, Alaska.

3 Establish a capability for long-term observations of atmospheric vertical structure, cloud properties, surface energy fluxes, precipitation, and ice characteristics at location(s) over the Arctic Ocean.

4 Long-term international collaborative support of the Polar Cap Observatory at Resolute, NWT, Canada.

5 Winter-over capability at Summit, Greenland, for high-elevation atmospheric measurements.

6 Development of instrument packages suitable for sensor deployment on icebreakers and specialized aircraft including remotely piloted aircraft, blimps, and tethered balloons.

Oceans/Sea Ice/Seafloor

7 *Healy*: The Arctic Icebreaker Coordinating Committee (AICC) should continue to hold open community meetings on the scientifically efficient use of the new *Healy* to emphasize a large degree of civil control during scientific missions (following UNOLS-type procedures). The AICC should be "empowered" with decision-making authority.

8 *Polar Star* and *Polar Sea*: Reevaluate their future scientific use in arctic science, especially in view of the commissioning of the *Healy*, by a science-based committee.

9 *ARV:* Evaluate the scientific capabilities and performance of the *Healy* after three years of operation. Reassess the scientific need for the *ARV* at this time.

10 The implementation of the SCICEX program provides the U.S. arctic research community with a unique opportunity to perform studies in a variety of disciplines producing scientific results that could not be obtained by any other means. Continue the ongoing workshops on the future use of submarines in arctic research with emphasis on maximizing the scientific output from these unique cruises (*e.g.,* prioritization of scientific problems to be tackled by submarine cruises; coordination of submarine time and capabilities between individual disciplines; new technologies to be implemented on the submarines used for arctic research; scheduling). Support continuation of the SCICEX program beyond its scheduled termination in 1999.

11 Work toward enhanced aircraft support from federal agencies.

12 Political involvement is needed to eliminate the severe problems obtaining permission for ship-borne studies in the Russian EEZ.

13 Long-term observations of the variability of the water masses, as well as sea ice, in the Arctic Ocean with high temporal resolution will be increasingly important; such measurements require the increased use of remotely operated, autonomous platforms (*e.g.,* AUVs, ROVs, floats, moored water samplers). The development of such tools, which are also useful for process studies on shorter time scales, should be accelerated.

14 Use of differential GPS should be made available for precisely locating specific sites (deployment and recovery of equipment and relocating of specific seafloor features).

Ice Sheets and Glaciers

16 Maintain the heavy-lift, ski-equipped LC-130 capability for access to the Greenland ice sheet.

17 Maintain the capabilities of the National Ice Core Laboratory to store and allow analysis of future cores to be collected.

18 Implement the capability for winter-over at the GISP2 Summit site.

19 Provide transportation to remote and high-altitude sites.

20 Provide portable two-way communications (such as INMARSAT) to field parties.

21 Enhance ice drilling technology by the development of:

- Directional, deep ice-coring capability to collect multiple samples from key depths;
- Safer, light-weight, intermediate, and deep drilling capability using the most environmentally friendly fluids and producing a high-quality core;
- Light-weight shallow drilling capability producing a high-quality core, with the option of alternative power sources (solar, wind) for high-altitude or remote operation;
- *In-situ* sampling thermal probe for accessing intermediate and deep ice;
- Improved hot-water drilling capability for bed access and vertical-strain-meter installation and auger capability for seismic shooting.

Terrestrial Research

Permanent Laboratories

22 Raise Toolik Field Station to a higher level of support capability (*e.g.,* improve housing—including winter housing, mess hall, field labs, electrical, and waste systems). Implement the recommendations of *Toolik Field Station: The Second 20 Years* (ARCUS, 1996).

23 Re-establish Barrow as a permanent year-round laboratory. Plan the steps necessary to acquire support facilities and set up a timetable for atmospheric, ecological, and geomorphological studies. Encourage development of a long-term management plan for the Barrow Environmental Observatory.

24 Provide helicopter support at Toolik and Barrow during summer sufficient to carry out funded research and insure that collected samples and equipment can be returned in a safe manner.

Mobile Field Camps and Transportation Nodes

25 Provide portable field shelters (Weatherport, Atco) with associated sanitary and living facilities.

26 Provide modular, transportable camp buildings and mobile field equipment including snow machines and a small portable field laboratory transportable by helicopter, dual snowmachines, and large aircraft.

27 Set up logistic facilitators at the regional level as needed in Alaska and Russia. These would establish contacts with federal agencies for shared logistics; establish and maintain contacts with local communities to assist with local hires and native expertise; centralize the permitting required by villages, boroughs, state, and federal agencies; establish suites of radios and a communications network for emergency situations; and coordinate aircraft use and communications for individual PIs.

28 Set up transportation centers at villages (coordinator, communication, storage warehouses, hotels, flying contracts, snow machines, coastal boats, field equipment) as needed at sites in Alaska, Russia, and Greenland.

Purchase Equipment for Shared Use of a Number of Projects

29 Paleolake studies must have several sets of high- and low-resolution seismic equipment, coring equipment, and gear for coring both shallow and deep arctic lakes, boats and motors for summer coring as well as snowmachines and skiffs for winter/spring coring operations.

30 Obtain a portable drilling rig to collect 30 m cores from permafrost.

Recommendations Specific to the Russian Arctic

31 Establish U.S. bank accounts in local Russian cities and a means for payment of services from these accounts.

32 Provide portable two-way intercontinental communciations (such as INMARSAT) to field parties.

33 Encourage cooperative agreements between the U.S. entities and local and regional governments across the Russian Arctic.

34 Make arrangements for access to proper maps and airphotos of Russian landscapes and coastal regions.

Cross-Domain Research

Social Sciences

35 Aid private enterprises in developing regional center accommodations, gear dumps, and processing facilities. Sign MOUs with the National Park Service (NPS), U.S. Fish and Wildlife Service (USFWS), and the Bureau of Land Management (BLM) for use of its regional dorms and gear. Identify surplus federal arctic gear (survival, camping, and research) and transfer it to regional

centers in the North. Develop MOUs with university and research facilities in other parts of the circumpolar north for low-cost accommodations and other facilities.

36 Develop MOUs with the U.S. Coast Guard and Alaska National Guard for helicopter use.

37 Assure that biohazards are handled only by trained experts.

38 Obtain surplus fishing boats for multidisciplinary research in coastal waters.

39 In the longer term, develop special multipurpose vessels for coastal research.

40 Develop MOUs with regional health authorities throughout Arctic Alaska for storing and transporting human tissue samples.

Contaminants

Specific recommendations for contaminant studies have been included under other disciplinary areas.

Marine Wildlife Biology

41 Improve facilities at UIC-NARL in Barrow and other coastal sites, including provision of snow machines with sleds, four wheelers, fuel storage, helicopter support, and freezer space.

42 Increase access to the ocean and sea ice via more joint operations with oceanographic projects and(or) development of the *Alpha Helix* replacement.

Table of Recommendations, Priorities, and Timelines

The following table on page 62-63 provides a quick look at the specific logistics recommendations. The recommendations in the table were prioritized based on several criteria, including feasibility of the logistics improvement, the maturity of both the necessary technology and the science questions it would benefit, the possibility of a dramatic improvement in science capabilities due to a logistics investment, the filling of major gaps in U.S. logistics capabilities, and the number of research disciplines that would be served. Each recommendation is given a priority of one, two or three stars (in the order of lowest to highest priority) and a time frame of short-, medium-, and(or) long-term. Many short-term priorities will continue into the medium- and long-term. Efforts for which the development process is clearly long-term may be recommended for action beginning within six months to two years. This is not intended to imply that two years is long-term.

In addition, many specific disciplinary recommendations are shared by, or will benefit, other disciplines. The community survey process made clear the extent to which distinct disciplinary areas have similar logistics needs. The column on the table marked 'Domain' indicates the cross-disciplinary recommendations. The area for which the recommendation was primary is indicated by a capital letter. Where other disciplines would benefit, they are noted by small letters. In many instances researchers from several disciplines stated the same or similar priority. In other areas, the indication of cross-disciplinary impact was added from subsequent discussions and reviews. Even a cursory scan of the table indicates the extent to which investments in single logistical areas will have payoffs in a number of others.

The numbers in the table correspond to the recommendations in the text starting on page 58.

Priority	Short-Term (6 months - 2 years)	Domain[1]
★★★ **Highly Appropriate for Immediate Implementation**	*Healy*: The AICC should continue to hold open community meetings on the scientifically efficient use of *Healy* to emphasize a large degree of civil control during scientific missions. **(7)**	a-O---
	Continue ongoing workshops on the future use of submarines in arctic research emphasizing maximal scientific output from these unique cruises. **(10)**	a-O--
	Enhanced aircraft support from federal agencies. **(11)**	a-OT-s
	Long-term observations of the variability of the water masses, as well as sea ice, in the Arctic Ocean with high temporal resolution require the increased development of remotely operated, autonomous platforms for long-term Arctic Ocean observations. **(13)**	--Otm-
	Maintain the heavy-lift ski-equipped LC-130 capability for access to the Greenland ice sheet. **(16)**	AG----
	Maintain the National Ice Core Laboratory to store and allow analysis of future ice cores. **(17)**	-G----
	Raise Toolik Field Station to a higher level of support capability. **(22)**	---T-s
	Provide helicopter support at Toolik Field Station and Barrow, AK, during summer field season. **(24)**	---T-s
	Provide portable field shelters (Weatherport, ATCO). **(25)**	a--T-s
★★ **Important, Requiring Further Technology Development or Science Planning**	Long-term international collaborative support of the Polar Cap Observatory at Resolute, NWT, Canada. **(4)**	A-----
	Political discussions to eliminate the problems of obtaining permission for ship-borne studies in the Russian EEZ. **(12)**	--O---
	Differential GPS should be made available for precisely locating specific sites. **(14)**	-gOt-s
	Implement the capability for winter-over at the GISP2 Summit site. **(5, 18)**	AG----
	Provide transportation as needed to remote and high-altitude sites. **(19)**	-G----
	Provide portable 2-way communciations (such as INMARSAT) to field parties. **(20, 32)**	-G-Tms
	Provide access to surplus fishing boats for multi-disciplinary research in coastal waters. **(38)**	-----S
★ **Important, Needing Novel Technology or Scientific Conceptual Development**	Enhance ice drilling technology by the development of: directional deep ice coring; safer, lighter-weight, shallow, intermediate, and deep drilling capability; in-situ sampling thermal probe for accessing intermediate and deep ice; and improved hot-water drilling capability for bed access and vertical-strain-meter installation. **(21)**	-G----

[1] A, G, O, T, M, and S: Recommended by Atmosphere, Ice Sheets and Glaciers, Oceans, Terrestrial, Marine Wildlife, and Social Sciences, respectively.
[1] a, g, o, t, m, and s: Will benefit Atmosphere, Ice Sheets and Glaciers, Oceans, Terrestrial, Marine Wildlife, and Social Sciences, respectively.

Priority	Medium-Term (2 - 5 years)	Domain[1)]	Long-Term (5 - 10 years)	Domain[1)]
★★★	Aircraft support for deployment of instrumentation and field study sites including small aircraft based from the primary facility. **(1)**	A-----		
	Science-based evaluation of the future use of the *Polar Star* and *Polar Sea* in arctic science. **(8)**	a-O-m-		
	Establish Barrow, AK, as a permanent year-round laboratory. Encourage development of a long-term management plan for the Barrow Environmental Observatory. Improve facilities at Barrow, AK, and other coastal sites including provision of snowmachines, sleds, four wheelers, fuel storage, helicopter support, and freezer space. **(23, 41)**	a--TMs		
	Provide modular, transportable camp buildings and mobile field equipment, including snow machines and a small portable field laboratory transportable by helicopter, dual snowmachines, and large aircraft. **(26)**	---T--		
	Establish U.S. bank accounts in local Russian cities and a means for payment of services from these accounts. **(31)**	a--T-s		
	Develop, through a variety of means, regional centers for accommodations, gear dumps, and processing facilities. **(35)**	---TmS		
	Develop MOUs with the U.S. Coast Guard and Alaska National Guard for helicopter use. **(36)**	---t-S		
	Assure that biohazards are handled only by trained experts. **(37)**	---t-S		
★★	Establish a permanent, primary facility for a broad spectrum of field studies. **(2)**	A--t-s	Establish a capability for long-term observations of atmospheric vertical structure, cloud properties, surface energy fluxes, precipitation, and ice characteristics at location(s) over the Arctic Ocean. **(3)**	A-----
	Establish logistic facilitators at the regional level as needed in Alaska and Russia. **(27)**	a--Tms		
	Establish transportation centers at villages or existing field stations. **(28)**	a--Tms		
	Develop sets of high and low resolution seismic and coring equipment, and other gear for coring shallow and deep arctic lakes (for shared use). **(29)**	---Tms		
	Obtain a portable drilling rig to collect 30 m cores from permafrost (for shared use). **(30)**	---Tms		
	Encourage cooperative agreements between the U.S. entities and local and regional governments across the Russian Arctic. **(33)**	---Tms		
	Make arrangements for access to proper maps and aerial photos of Russian landscapes and coastal regions. **(34)**	---Tms		
★	Develop instrument packages suitable for sensor deployment on icebreakers and specialized aircraft. **(6)**	A--t--	Evaluate the scientific capabilities and performance of the *Healy* after three years of operation. **(9)**	a-O---
	Develop MOUs with regional health authorities throughout arctic Alaska for storing and transporting human tissue samples. **(40)**	-----S	Develop special multi-purpose vessels for coastal research. **(39)**	-----S

[1)]A, G, O, T, M, and S: Recommended by Atmosphere, Ice Sheets and Glaciers, Oceans, Terrestrial, Marine Wildlife, and Social Sciences, respectively.
[1)]a, g, o, t, m, and s: Will benefit Atmosphere, Ice Sheets and Glaciers, Oceans, Terrestrial, Marine Wildlife, and Social Sciences, respectively.

Summary

A tremendous amount of high-quality research has been done in the Arctic using available logistical assets. The limitations of U.S. logistical capabilities, however, have slowed our understanding of larger scale processes in this region. Because of the difficult and remote nature of much of the Arctic, scientists have been "looking for their keys underneath the lamp post" to a certain extent. Investigators have been doing research where and how they could (under the lamp post), not necessarily in the most important places (where the keys might be) or in the most efficient way. Major gaps in our knowledge persist because of inadequate logistical support. Substantial progress will only be made if investigators' logistical needs are identified and addressed. Much of the needed capability already exists in the resources of the federal government.

A remarkable outcome of the community surveys and meetings that went into this report is the broad consensus between otherwise disparate disciplines in the needs for logistical support. All scientists working in the Arctic will benefit from improved access to research sites, increased development and use of autonomous instrumentation, greater attention to health and safety questions, assistance with involving local communities in research, and better international coordination. These five general recommendations outline a coherent logistical support strategy for U.S. research. The implementation of each of these general recommendations requires both improved coordination within and among scientists, agencies, communities, and nations, and targeted investments in physical logistics assets, as described in this report.

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Appendix B

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Charge to the ARCUS Arctic Logistics Working Group from the U.S. Arctic Research Commission

Appendix C

The U.S. Arctic Research Commission has long been concerned with the state of logistic support for research activities in the Arctic. In conversations with ARCUS it became clear that it was necessary for the academic community working in the Arctic to come to a consensus concerning their logistics needs. For this reason, the Commission requested that ARCUS proceed to formulate this consensus and supplied financial support for the project.

The charge to ARCUS from the USARC is to describe the science-driven logistics needs for the U.S. Arctic academic community for the next five years, to outline the needs for the subsequent five years and to focus on U.S.-based academic research, wherever such efforts may need to operate in the circumpolar north. The Commission has asked ARCUS to assess current logistical resources for arctic research and evaluate the limits placed on research by current logistical resources. ARCUS has also been asked to canvas their membership and other arctic researchers in the U.S. academic research community for current and future needs, consult existing evaluations of logistical needs, and seek wide consultation with the arctic research community and member institutions in the process of developing a final draft.

The Commission has asked ARCUS to consider the direct and indirect impacts of changes in federal support on current arctic research support and develop a sequence and scope for improving logistics and research facilities in three categories: marine, terrestrial, and social research with due consideration for the limits on funding and practicality while maintaining a clear focus on the scientific challenges currently unmet in the Arctic. By bringing the diverse views of the academic community together in this report, ARCUS will be providing a vital central focus for progress in the support of arctic research.

Procedures for Gathering Community Input

An important element of this assessment of the logistics available to the U.S. academic arctic research community is the involvement of as large and diverse a portion of the scientific community as possible. In order to achieve this goal, the following procedure was followed:

- ❖ A Logistics Working Group (LWG) was appointed by ARCUS; members represent a variety of scientific disciplines, geographic regions in which research is conducted, and institutions conducting arctic research.
- ❖ The creation and charge of the LWG was announced throughout the winter of 1995 and spring of 1996 in *Witness the Arctic* (the ARCSS newsletter published by ARCUS), through e-mail announcements to the arctic research community, and at various arctic research meetings. Care was taken to reach as many scientists as possible from the fields of natural and social sciences.
- ❖ The plans of the LWG were outlined during the 8th Annual Meeting of ARCUS, held jointly with the U.S. Arctic Research Commission in Washington, DC, in March 1996.
- ❖ A survey (mainly via electronic mail) of the logistical needs as perceived by the arctic research community was conducted. A 12% response to the initial survey distribution was received, approximately 110 responses.
- ❖ A workshop on Arctic logistics was convened at Snowbird, Utah, on May 4, 1996, in the context of the NSF ARCSS Program All-Investigator Workshop. The workshop included approximately 70 participants, nearly half of whom had not submitted a survey response. The preliminary results of the survey were presented and five working groups, defined by disciplinary concerns, used the survey results as the starting point for discussions of the logistical requirements in various fields of arctic science.
- ❖ The recommendations from the workshop and the results of the survey were posted on the ARCUS WWW site in early August 1996. This allowed further community input before preparation of the draft of this report. The logistics information posted on the WWW received heavy use prior to the LWG meeting in late August.
- ❖ Several review drafts of the report were posted on the ARCUS WWW site between September 1996 and May 1997; significant revisions and additions made by the thirty contributors listed in Appendix B.

The LWG assembled the present report for the USARC and the U.S. agencies funding arctic research. The final report will be posted on the ARCUS WWW site at <http://arcus.polarnet.com>. The report is envisioned as a first step toward a community-based assessment of the arctic logistics needs. It is viewed as a living document and will be updated as necessary.

Existing Arctic Logistics

U.S. Logistics for Marine Research in the Arctic

Drifting Ice Camps

The U.S. currently has very capable support for drifting ice stations. Each of three available providers are fully capable of deploying at least two 20-person ice stations at any given time. Stations have been routinely utilized for a variety of oceanographic, meteorological, and sea-ice investigations focused on intensive process studies. Stations can be deployed essentially anywhere in the Arctic Ocean.

Aircraft

U.S. commercial and military as well as foreign aircraft have supported ice camps and deployed autonomous instrumentation over much of the Arctic Basin. Frequently used aircraft are the Twin Otter, Caribou, C-130, and a wide array of helicopters. Larger aircraft such as the C-141 have been used to stage airdrops of fuel, equipment, and supplies for drifting ice camps.

Oceanographic Vessels

USCGC Polar Sea *and* Polar Star

The U.S. has two 399-foot Polar Class icebreakers operated by the Coast Guard. The icebreakers have supported a fair number of oceanography, geology, geophysics, sea-ice, and biology studies. They have proven successful at penetrating deep into the Arctic Basin in company of another capable icebreaker, but have also demonstrated that their propulsion system is extremely vulnerable in heavy ice. The vessels are equipped with minimal internal laboratory facilities, but can accommodate seven portable laboratories on deck. They have two over-the-side hydrographic winches, a coring or trawl winch on the stern and several heavy-lift cranes. Crew size varies from 160 to 180, and up to 35 scientists can be berthed. Unless science can be accomplished on an opportunistic basis in conjunction with a Coast Guard training or engineering testing program, the cost is approximately $20,000 per day for icebreaker use. Both of these ships have been useful in providing a base of arctic operations that would otherwise be unavailable. However, the lack of long-range continuity, personnel rotation, and frequent breakdowns have made it difficult to build intensive, multi-year, multi-investigator science programs.

R/V Alpha Helix

The 133-foot oceanographic research vessel *Alpha Helix* is owned by the National Science Foundation and operated by the Institute of Marine Science, University of Alaska Fairbanks. Home port for the *Helix* is the Seward Marine Center, in Seward, Alaska. The R/V *Alpha Helix*, which is 30 years old, is maintained and used as a year-round platform suitable for oceanographic research on the open ocean and in

Alaska's shelf and coastal waters. Its modestly ice-strengthened hull severely limits its operations in seasonal sea ice and in areas adjacent to the numerous tidewater glaciers occurring in Alaska's coastal zone. The vessel provides living quarters for 15 scientists and a crew of nine. Working spaces include a large general-purpose laboratory opening to the working area on the stern, an electronics room, a walk-in freezer, a temperature control room, a machine and wood shop, a library, and a small wet laboratory. The working space aft is served by a hydraulic crane with extendible boom, a stern A-frame, a hydrographic winch and conducting cable, and a deep-sea winch. A bow thruster is available for station keeping at sea.

USCGC Healy

The *Healy* is under construction at Avondale Industries in New Orleans, LA and is due to be launched in late 1998. This 420-foot icebreaker will have significantly expanded science facilities over the Polar Class vessels in both internal laboratories and over-the-side equipment. Crew size is slated to be 75 with berthing for 35 scientists. The Coast Guard has described its primary mission as a high-latitude research platform. Costs for use of the *Healy* are expected to be similar to those for the Polar Class.

U.S. Navy Submarines

U.S. Navy submarines have been successful on three submarine science cruises (SCICEX). The submarines have the advantage of accessing virtually any part of the Arctic Ocean permitted by water depth. Currently, the Navy restricts the science cruises to that area of the Arctic Ocean which does not infringe upon the EEZ of other nations, but this is still a major portion of the Arctic Basin. The submarines have been used for studies of hydrography, geochemistry, gravity, bathymetry, and biology, as well as to deploy autonomous instrumentation. Equipment installations requiring ice-hardening and through-hull penetrations can be expensive and require long lead times. The operational costs of the submarine cruises have been provided by the Navy. Additional cruises are scheduled each year through 1999.

International Logistics for Marine Research in the Arctic

Canada, Germany, Sweden, and Russia all have very capable research icebreakers. These are not easily available to U.S. scientists. Access to the German and Swedish ships is only open to U.S. scientists who are collaborating with scientists from those countries. The Canadian and Russian ships are available for charter. Norway has commercially available ice-strengthened vessels, which are suitable research platforms in marginal ice zones.

U.S. Logistics for Terrestrial Research in the Arctic

The construction of the Trans-Alaska Pipeline made it possible to carry out research in northern Alaska along the transect of the North Slope of the Brooks Range provided by the Dalton Highway, from Prudhoe Bay at the north, through Happy Valley in the foothills, to Toolik Lake in the foothills at the south. Most of the research is supported by the University of Alaska's Toolik Field Station (TFS). Some research is based at Happy Valley or Prudhoe Bay where commercial hotel room and board is available.

Toolik Field Station

The Toolik Field Station is a national facility for arctic research operated by the Institute of Arctic Biology. It is located at 68° 38' N, 149° 38' W, on the shore of Toolik Lake in the northern foothills of the Brooks Range, 400 miles north of Fairbanks and 125 miles south of Prudhoe Bay. The Station provides logistics support to academically sponsored basic research within the Toolik Long-Term Ecological Research (LTER) Site. This includes approximately 360 km^2 encompassing two watersheds: the Kuparuk River and the Toolik Basin. The Toolik LTER is designated by the U.S. Department of the Interior as a Research Natural Area and an Area of Critical Environmental Concern. Over the two decades since it was founded, the TFS and adjacent regions have been the sites of many biological and hydrologic studies. Much of the data gathered since 1987 on streams, lakes, and tundra is included in the databases (on the WWW) of the LTER and ARCSS programs.

The Station is the only active national research facility for study of terrestrial biology, freshwater biology, geology, etc., in the U.S. Arctic and allows major research programs to proceed without construction and maintenance of support facilities. The logistics capability of the Institute of Arctic Biology and the Station gives projects the option of study sites throughout the Dalton Highway corridor north of Fairbanks.

Up to 50 investigators may be housed at TFS. TFS is funded by a daily charge for each investigator of $150. Room and board, laboratory space, and a round trip to Prudhoe Bay are provided. These per diem charges are included in each investigator's grant budget or are paid for by a large project (*e.g.,* the NSF ARCSS Program). Several large projects have their own trucks for transportation along the Dalton Highway, again paid for through project grants. Each project must provide clothing, supplies, and equipment for researchers.

In recent years, the NSF ARCSS Program has provided commercial helicopter support to allow scientists to carry out measurements along the entire Kuparuk River basin. Total cost was approximately $200,000 at a cost of about $750 per hour. This expansion of the ability to look at ecosystems and processes over a larger area increased the detailed knowledge coverage from about 10 km^2 to 8,000 km^2 and also drastically expanded the perspective of the scientists involved.

Over the past 20 years the growth of TFS has been rapid, but driven largely by the short-term needs of individual projects and the limited availability of funds. Comprehensive long-term planning and funding for TFS itself has lagged behind the growth of research programs. This situation has been addressed recently; a priority list for facilities upgrades for TFS has been drawn up through a workshop organized by ARCUS (1996). If planned upgrades are funded, the TFS will evolve into a world-class field station able to support research in the immediate area as well as to provide logistics for a wider region of the North Slope.

Appendix E

Barrow

UIC-NARL (Ukpeagvik Inupiat Corporation–NARL). The Barrow village corporation took over ownership and management of the Naval Arctic Research Laboratory from the federal government. Numerous buildings in the facility have been upgraded and made available to research and educational activities that take place throughout the year. Lodging is available onsite at the UIC-NARL Hotel and meals are available onsite at the Ilisagvik College residential cafeteria. Telecommunications facilities support laboratory and office spaces used by research projects. Walk-in freezers supplement cold and warm storage and workrooms. A logistics supply base is being built, currently including tents, Weatherports, insulated tents, generators, snow machines, ATVs, Zodiacs, and other field support items. New science-dedicated longterm residential space will be constructed by Spring 1997. Two foreign countries, Japan and China, are investigating constructing research labs at UIC-NARL.

Ilisagvik College. Ilisagvik College, located at UIC-NARL, is developing a northern focus for academic studies. Primarily two-year plus vocational education, Ilisagvik is moving to some four year academic programs. Ilisagvik students are encouraged to work with scientific research projects, and visiting researchers are encouraged to teach 1-, 2-, and 3-credit courses (for 1, 2 and 3 weeks) during their visits to the North Slope.

Barrow Environmental Observatory (BEO). BEO covers 30 km^2 of land near the Chukchi Sea and adjacent to Elson Lagoon. The BEO is land belonging to the Natives of Barrow through their village corporation, UIC. They have dedicated the land to scientific research and taken it out of development. The National Science Foundation has provided some funds for survey work and signage and has recently signed a Cooperative Agreement with the Barrow Arctic Science Consortium to manage the preserve. A project is being started to gather and make available to today's researchers the raw data and project reports on the five decades of previous research in and around the BEO.

Arctic Research Facility (ARF). The North Slope Borough, through its Department of Wildlife Management, maintains a small research station in Barrow. The Borough's Arctic Research Facility is located at the UIC-NARL complex. The ARF can provide bunkhouse-type lodging and other logistical support (snowmachines, small boats, radios, heavy clothing, etc.) for up to 20 people. Its primary purpose is to support Borough field efforts regarding censusing bowhead whales, and supporting basic fisheries and waterfowl studies in the general Barrow area. The ARF is available for use by other scientists on a limited basis and over the years has supported a wide range of visiting scientists.

Barrow Arctic Science Consortium (BASC). BASC has been designated by UIC to manage the Barrow Environmental Observatory. BASC also manages UIC's science facilities at UIC-NARL. BASC is a logistics services provider to research projects. Technical support, guides, and bear watch guards are available through BASC. BASC arranges community outreach lectures and public meetings to connect the northern public with visiting researchers and helps get local students and residents involved with projects. A current NSF-funded archaeology project has negotiated community-wide access to a cache of surplused federal camp support equipment and stored it in Barrow, but there are no maintenance funds for the materials. BASC is negotiating to acquire additional surplus equipment, up to and including tracked vehicles. Support for scientific projects at Barrow is available through BASC (working with the UIC Real Estate Science Division), on a reimbursable basis. They are located at the NARL facility about 3 km north of the village of Barrow. They can provide snow machines, vehicles, warm and cold laboratory space, office and storage space, lodging, field shelters, field assistance, and expediter services. There are several hotels and restaurants, as well as car rental and other commercial services, located in the village of Barrow. There is a hotel at the NARL facility and a cafeteria is located in the main building at NARL site which serves the students at the local college. The office and laboratory space available for rent from BASC is located in the same building.

National Oceanic and Atmospheric Administration (NOAA). Since 1973 the NOAA Climate Monitoring and Diagnostics Lab has maintained what is perhaps the premier climate change research facility in the Arctic, the BRW Observatory. Support is provided by a 2 person staff to over 40 projects from NOAA and around the world. The most recent agreement is with the Department of Energy/ Atmospheric Radiation Measurement (DOE/ARM) program as the host site for the instrumentation of the Cloud and Radiation Testbed site for the North Slope of Alaska (CART/NSA). ARM is part of an effort sponsored by the Department of Energy to resolve scientific uncertainties about global climate change. The CART site will employ sophisticated radiometric and associated instrumentation and data telemetry systems and is expected to be deployed in the spring of 1997. It is anticipated that the Barrow CART site will be come a focal point for atmospheric and ecological research on the North Slope.

NSF Polar Program's UV Spectroradiometer Network Barrow, Alaska Site. Instrumentation permanently installed at UIC-NARL since 1990 automatically records high-resolution UV data for a world-wide study of ozone depletion, supplementing three sites in Antarctica, one in South America and one in San Diego. Studies cover the effects of ozone depletion on terrestrial and marine biological systems and development and verification of models of atmospheric light transmission and the impact of ozone depletion.

Arctic Logistics and Information Access and Services (ALIAS)

Although there are many great successes in U.S. arctic research accomplished with the logistics described above, new challenges (larger field programs related to system science approach; integration of natural and social sciences; the increased logistics capability of other countries) require adjustments of the existing logistics towards a modern, efficient, and sustained arctic logistics accessible to all U.S. academic research institutions.

One effort to address these needs, a logistics information clearinghouse, grew out of the U.S. Arctic Research Commission recommendations and discussions within Interagency Arctic Research Policy Committee (IARPC) on how to provide the arctic research and development community with the most cost effective support for its activities. The Arctic Logistics and Information Access and Services (ALIAS) is available on the Internet at <http://www.nsf.gov/od/opp/arctic/logistic/start.htm>.

The goal of ALIAS is to link existing sources of information from arctic nations, government agencies, universities and research institutions. Information is presented by geographic location (maps), subject index, research area, logistics providers, and external links. The ALIAS home page is still evolving and holds great promise for arctic researchers.

Individual Arctic Logistical Networks

At present, many individual investigators are dependent upon their own arrangements and equipment to carry out research. Cold-weather gear, medical preparations, guns, and over-snow transportation may not even be considered as allowable expenses under many funding programs. Few dedicated logistical resources are currently available to individual investigators (including social scientists, biologists, geologists, etc.) in northern Alaska or the Russian Far East.

With experience, PIs typically establish their own means of networking with local residents, commercial bush pilots, and sometimes with federal agencies for assistance with remote transportation issues and for communications. For example, it is sometimes possible for PIs to cheaply buy a few hours or days of helicopter time on an existing federal contract (NPS, USGS, or BLM) if time is available in a particular week and the PI has some knowledge of helicopter availability via contacts in a particular agency. However, because federal dollars for arctic research by federal agencies are being decreased or have become nonexistent (*e.g.,* U.S. Geological Survey has few field programs compared to only ten years ago) opportunities for "piggybacking" helicopter or fixed-wing charters on existing contracts is very limited. In cases where PIs have befriended local agencies, PIs are able to "borrow a truck" on a limited-use basis or buy cheap bunk space otherwise intended for summer employees.

Despite existing levels of technology it is still not uncommon for individual field parties to work in remote regions of the Arctic for days or weeks at a time without adequate radio communications for emergencies. While some have used, rented, or borrowed CBs, VHF, or SBX-11 types of radios, it is often difficult, without proper networking in local villages, for PIs to secure people or local offices within the villages to "listen" for them at regularly scheduled intervals. Safety issues, whether they involve risk from exposure to arctic weather, bear attacks, or hazardous work at sea, on lakes or rivers in small boats, are currently left up to the discretion of individual PIs. No formal arrangements exist for medical evacuation insurance and all costs are the responsibility of the PIs. Proper training of students in the safe use of guns and in arctic survival is up to the discretion of individual PIs and their home institutions.

Subarctic Research Facilities

Although not itself located in the Arctic, the University of Alaska campus in Fairbanks has many research facilities available which support arctic research. These facilities, which are located in or near Fairbanks unless otherwise noted, include:

Seward Marine Center in Seward is a coastal research and teaching facility which includes a 4,000 square-foot laboratory containing wet laboratory space with running sea water, a large warehouse/office complex, a public education building and auditorium, housing for visiting faculty and students, and covered outside seawater tanks. The Center is home port for the research vessel *Alpha Helix*.

West Coast National Undersea Research Center is one of six regional centers of the National Undersea Research Program of NOAA, which facilitates undersea research programs along the West Coast and in the Arctic and Antarctic by making submersible assets and ROV's available to investigators at no cost through a peer-reviewed proposal process.

Kasitsna Bay Laboratory's facilities on Kachemak Bay include two 400 square foot laboratories and two 9 x 40 foot trailers equipped as laboratories, living accommodations for 18 people, a storage and maintenance shop, a seawater system, and several small boats.

Fishery Industrial Technology Center in Kodiak conducts a research and development program and provides technology transfer and training to enhance the economic development of the Alaskan fishing industry. Facilities include a pilot processing plant, laboratories for engineering, chemistry, biogeochemistry, and microbiology, and a sensory evaluation kitchen.

Poker Flat Research Range is used primarily for scientific sounding rocket launches whose mission objectives usually involve auroral and polar middle-upper atmosphere research. Class I downrange observatories containing magnetometers, riometers, scanning photometers, all-sky cameras, and interferometers are located at Fort Yukon, Barter Island, Elmendorf Air Force Base, and Svalbard. Class II observatories containing magnetometers and riometers are located at Bettles, Kotzebue, Barrow, Eagle, Arctic Village, Fort Yukon, College, and Talkeetna, Alaska as well as Inuvik and Cape Parry, Canada. Poker Flat's Climate Change Monitoring Center routinely measures temperature and dew point, atmospheric ozone, atmospheric carbon monoxide, aerosol optical scattering, and concentration of light-absorbing soot.

College International Geophysical Observatory is part of the USGS National Geomagnetic Information Center and participates in the Global Magnetic Observatory Network. Current programs include geomagnetism, seismology, earth currents, gravity, galactic noise, global positioning, hydrology, and meteorology.

Alaska Earthquake Information Center analyzes data from the joint UAFGI/USGS network which incorporates more than 160 stations, most of which are located in central and southern Alaska.

Alaska Volcano Observatory is a cooperative organization that monitors Alaska's hazardous volcanoes, focusing on the Cook Inlet region.

Alaska Synthetic Aperture Radar Facility processes data from the European Space Agency's ERS-1 and ERS-2 satellites and Japan's National Space Development Agency's JERS-1 satellite. In the near future, SAR data will be available from the Canadian Space Agency's RADARSAT and the Japanese Advanced Earth Observation Satellite. The Geophysical Processing System, using SAR input, produces ice motion, ice classification, and ocean-wave spectra products. The Geo-Data Center holds many complementary data sets from Landsat, NOAA satellites, High-Altitude Photography, and many USGS maps.

Arctic Region Supercomputing Center consists of a CRAY Y-MP and T3D, Silicon Graphics Inc. Onyx XL visualization server, robotic tape silo, and disk arrays.

Lidar facilities. A STEL Rayleigh/Mie lidar, deployed at Sheep Creek, is one of three stations in the Japanese Arctic Lidar Network that measures stratospheric and tropospheric aerosol and chemical processes at Alaska, Eureka, and Svalbard. A resonance lidar at Poker Flat Research Range measures mesospheric metals and aerosols and stratospheric densities and aerosols. A Doppler-Rayleigh lidar system that will measure winds and temperature as well as aerosol in the stratosphere and mesosphere is scheduled for deployment at Poker Flat in the late 1990s. These three lidars provide measurements of the atmosphere from the ground to 110 km and together allow studies of coupling between the troposphere, stratosphere, and mesosphere (*e.g.,* tropospheric foldings, sudden stratospheric warmings, wave-mean flow interactions).

Alaska Agricultural and Forestry Experiment Station includes the Fairbanks Research Center, Palmer Research Center, and Delta Junction Research Center which have facilities for preparation of soil, plant, and in some cases animal materials for analyses needed in research on agronomy, horticulture, forestry, soil and water pollution, and animal science.

Bonanza Creek Long-Term Ecological Research Site includes representatives of each of the major boreal forest types occurring in central Alaska. Because it is one of the sites in NSF's Long-Term Ecological Research Program, both climate and vegetation parameters are monitored regularly.

High-Technology Plant Growth Facility was designed to facilitate experiments on the effects of variation in air and soil temperature and other environmental factors on plant performance. The greenhouse is unique in its independent control of air and soil temperatures which has special relevance to Arctic ecosystems.

Large Animal Research Station allows research on large wild ungulates in captivity and has a central handling facility and equipment for large animals, research barn, hay barn, feed and bedding storage units, offices, and living quarters on 150 acres.

Halibut Cove Research Station near the town of Homer can house eight people, has a kitchen, wood stove, electricity, refrigeration, water supply, and outdoor plumbing, and is accessible only by boat. Four skiffs are available on-site for use by researchers.

Cantwell Reindeer Research Station in Cantwell consists of two 10 x 55 foot mobile homes and a large log cabin accommodating six researchers. Water and power is available. The mobile homes are heated and have limited kitchen facilities. Some heated and unheated storage is available on-site, and a large building provides dry laboratory space.

High-Latitude Monitoring Station

The High-Latitude Monitoring Station is located on Elmendorf Air Force Base in Anchorage and provides 24-hour continuous monitoring, processing, archiving and transmission of solar geophysical data to DOD and non-DOD federal agencies. Primary monitoring systems consist of riometers, magnetometers, a Total Electron Content system, and the Anchorage Auroral Radar System. The systems are designed to provide the Air Force Space Command with observations of auroral activity.

International Logistics for Terrestrial Research in the Arctic

Greenland

The U.S. currently has very capable logistical support for land- (coastal and ice sheet) based research in Greenland. The U.S. presence in Greenland is supported through international agreement with Denmark, and is based on collaboration in defense and scientific realms. All U.S. research conducted in Greenland is reviewed annually and must be approved by the Danish Commission for Scientific Research in Greenland to ensure compliance with Danish and Greenlandic Home Rule Government safety, environmental protection, and other regulations, and to ensure that U.S. researchers are collaborating with Danish colleagues to the fullest extent possible. The Danish Polar Center serves as the clearinghouse for these collaborations.

The current U.S., land-based logistical support system is based on open access to and utilization of a combination of Danish government-sponsored research programs, Danish and Greenlandic governmental and civilian coastal and air transportation system infrastructure, the U.S. Department of Defense presence at Thule Air Base, the U.S. heavy-lift LC-130 air-support capability, and U.S. federal agencies' investments in research facilities and support services at coastal and ice-sheet locations. The Danish government is actively supporting coastal geological, meteorological, biological, archaeological, and social scientific research programs that include U.S. investigators. The Danish Government and European Science Foundation are currently supporting a major European ice-core drilling and analysis program on the north central ice sheet, the North Greenland Ice Core Program, with a multiyear summer camp and heavy-lift and light, fixed-wing air support that includes opportunities for participation by U.S. investigators.

Kangerlussuaq. At Kangerlussuaq, (formerly Søndrestrøm Air Base), the Greenland Home Rule Authority supports both individual investigators and large-scale research efforts by providing the Kangerlussuaq International Science Support (KISS) Center. These year-round modern facilities, which became fully operational in the summer of 1995, provide for research and related education of all interested parties at moderate costs. Living accommodations including housing, dining facilities, laundry, etc., are available, as well as laboratories, classrooms, snow machines, four wheelers, and storage. Small charter aircraft are based at the adjacent Kangerlussuaq airport, which also has direct international connections. Kangerlussuaq has a long tradition as a base for geophysical and glaciological research. The center is also appropriately located for general ecological research in this uniquely dry arctic biotype close to the inland ice. Muskoxen are particularly abundant in the immediate area and caribou at a much lower density. Opportunities exist for collaborative research with Danish and Greenlandic scientists.

Nuuk. At Nuuk, the Greenland Lands Museum and Archives, the Office of Research, and the University of Greenland provide assistance to U.S. investigators collaborating with Danish counterparts. The Royal Danish Air Force, army, and Greenlandic Airport Authority provide air support facilities at remote north and east Greenland coastal sites such as Station Nord, Danmarkshavn, Constable Pynt, and SIRIUS patrol depots, that provide staging opportunities for coastal geological and archaeological investigations and for ice-sheet-based glaciological research efforts.

Zackenberg. The Danish Polar Center is establishing an arctic research station at Zackenberg in northeastern Greenland (74° 28' N x 20° 34' W) to be fully operational in the summer of 1997. The year-round facility is available as a research base for arctic research in the physical and biological sciences. The area is biologically rich for such a high altitude in eastern Greenland. The research station can accommodate up to about 20 scientists and has laboratory and dining facilities, satellite computer connections, remote weather stations, small boats, four-wheelers, and aircraft access. The station provides firearms and radios for personal safety. The Danish Polar Center coordinates all research activities at Kangerlussuaq and Zackenberg. Details can be obtained through the Danish Polar Center home page <http://www.dpc.dk>.

Thule Air Base. The U.S. military presence and infrastructure at Thule Air Base provides a scientifically underutilized resource available to U.S. investigators. The NSF has recently taken possession of much of the Navy field equipment previously used in SPAWAR experiments. U.S. Navy- (SPAWAR), NSF-, and NASA-sponsored research programs share a logistical staging and warehouse facility on the base. An InterService Support Agreement between NSF and HQ Space Command provides the foundation for civilian scientists' (supported by multiple federal agencies) access to and support from the air base. The location of Thule in the northwest of Greenland provides unique staging opportunities for research in the high arctic terrestrial regions, Arctic Ocean, and other marine environments.

109th Airlift Wing. The U.S., heavy-lift, ski-equipped LC-130 capability provided by the 109th Airlift Wing of the New York Air National Guard provides the U.S. and its Danish collaborators with a unique logistical support capability. The 109th AW provides the U.S. with access to virtually all points in the interior of the Greenland ice sheet. The ability to transport up to 30,000 lbs. of payload to prepared skiway locations and up to 10,000 lbs. to remote unprepared sites enables researchers to implement projects ranging from major, deep, ice-core drilling efforts to highly mobile lightweight geophysical and glaciological surface traverses. The 109th AW now includes airdrop capability as an optional means of supporting remote ice-sheet and sea-ice research efforts. The heavy-lift capability of the 109th AW is often used in tandem with commercially available light, fixed-wing aircraft stationed on the coast or at remote ice-sheet research camps.

Other U.S. Facilities. The U.S. maintains several major ongoing research facilities and logistical support service contracts to support U.S. research in Greenland. In Kangerlussuaq, the NSF maintains a radar facility operated under contract with SRI, and a field operations center including a warehouse of field equipment, vehicle fleet and maintenance facility, and seasonal field operations management staff operated under contract with the Polar Ice Coring Office (PICO) at the University of Nebraska-Lincoln. At the site of the recently completed NSF-sponsored Greenland Ice Sheet Project Two at the summit of the ice sheet, the NSF has maintained under the PICO contract a major camp facility and skiway in support of glaciological and atmospheric investigations. The U.S. currently has the building and camp infrastructure technology available to enhance the Summit site, making it capable of supporting year-round operation.

Russia

Opportunities. The recent collapse of Communism in the Soviet Union has provided new and exciting possibilities for bilateral projects and access to the Russian Arctic landscape by U.S. researchers. Soviet policy sought to develop northern resources for national self-sufficiency and security. Major scientific facilities and platforms were built in association with these developments. Soviet scientists pioneered the use of drifting ice stations and aircraft for studies of the Arctic Ocean. Despite the breakup of the Soviet Union, many important research resources remain.

Concerns. The unsettled nature of the existing Russian political structure and economy poses great challenges to individual investigators. Before launching into any project, it is absolutely necessary for U.S. PIs to establish contacts with Russian scientists who are well established in their home institutions. Documents outlining the nature of the collaborative work and the expectations of both U.S. and Russian scientists need to be carefully crafted. Most importantly, it is necessary for the Russian institutes to be mindful of local political documents or permitting necessary for carrying out research of various types. PIs must be prepared at all times for unexpected political problems derailing projects at the last minute, for reasons over which U.S. citizens have no control. The success of any research project is highly dependent on the networking and back-room infrastructure that has been established by the individual research institutes and the researchers working at those institutes.

Logistical arrangements are almost always difficult to negotiate in the Russian Arctic. Due to the lack of funds for science in Russia, most U.S. investigators must pay for nearly all expedition costs outside of salaries for Russian collaborators. Across most of the Russian arctic, all transactions for food, lodging, or transportation must take place in cash requiring PI's to place themselves and their students at risk by traveling with large sums of money (up to $10,000 – $15,000) in their pockets. Commonly, U.S. PIs are faced with unexpected costs, such as elevated costs for airline tickets for visitors bearing American passports or new "science fees" created by local government officials.

Working in remote regions of Russia almost always means working without any radio contact or safety net for emergency situations. Likewise, it usually means working without adequate air photos and maps even though they probably exist. Years of strict control over maps and air photos by the Communist government has not been undone by the establishment of democracy in Russia, and it is still possible to be jailed for attempting to leave Russia with detailed maps of 1:100,000 or larger. In many areas, local border guards or coastal patrols have been known to make their own "laws" about where researchers are allowed to conduct research, despite proper documents. Many groups working in Russia in recent years report having their passports confiscated temporarily by local officials.

Fennoscandia

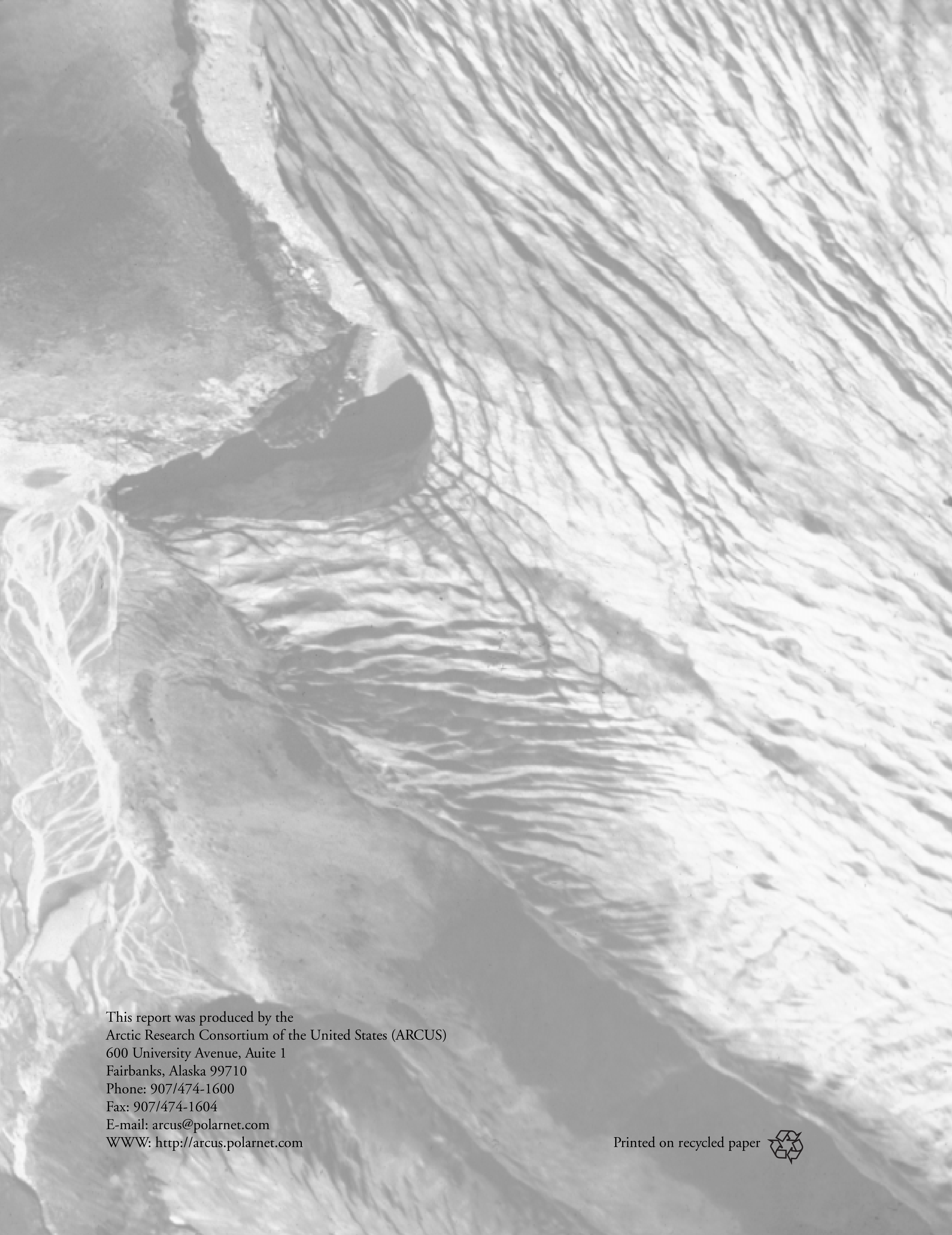
The research stations in the Fennoscandian countries are directly supported by their governments and are of very high quality and capability. Access for U.S. investigators to research sites in Fennoscandian countries (other than Greenland) is often provided gratis or at low cost, but is done so based upon individual cooperative relationships built up over several years. The lack of parallel U.S. facilities makes reciprocity unusual which presents ongoing difficulties to U.S. researchers dependent on these relationships.

Norway: Excellent research facilities exist in Svalbard at 79° N under the jurisdiction of the Norwegian government. The Department of Arctic Biology at the University of Tromsø maintains research facilities near the town of Longyearbyen and its international airport. Collaborative research with scientists from other countries is encouraged, and opportunities exist for year-round research on both terrestrial and marine arctic ecosystems. Ny-Ålesund is an international arctic environmental research and monitoring station on Svalbard which can accommodate up to 150 persons. The station is open year-round with several commerical flights to its airport daily in summer and one in winter. It has modern telecommunications and harbor facilities. In Norway proper, the northernmost university in the world is the University of Tromsø at 70° N, which has extensive research facilities and a medical school.

Sweden: Abisko Scientific Research Station is a year-round research facility that can house up to 80 workers. Established in 1903, it operates under the auspices of the Royal Swedish Academy of Sciences and is accessible by rail and road. The station is situated in a nature reserve adjacent to a national park. The emphasis of staff research is plant ecology and meteorology.

Polar Continental Shelf Project—Canada

The Polar Continental Shelf Project (PCSP) has provided logistics support for many years for scientists in the Canadian Arctic in a manner that could serve as a model for U.S. efforts. Two base camps are maintained, Resolute on Cornwallis Island and Tuktoyaktuk in the Mackenzie Delta. PCSP provides room and board at its base camps, makes special equipment available on loan, and coordinates the establishment of remote field camps. It provides efficient air transport through long-term chartering with experienced pilots and has a radio communications system through which contact is maintained with remote field camps and aircraft. PCSP has been supporting approximately 200 scientific projects each year. U.S. scientists have used PCSP's facilities and services on a space-available basis for nominal fees. PCSP's services are now threatened by the extensive budget cuts by the Canadian government; logistics support for arctic research through PCSP has been severely curtailed.



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