VOLUME 12 FALL/WINTER 1998

ARCTIC RESEARCH OF THE UNITED STATES

INTERAGENCY ARCTIC RESEARCH POLICY COMMITTEE

About the Journal

The journal *Arctic Research of the United States* is for people and organizations interested in learning about U.S. Government-financed Arctic research activities. It is published semi-annually (spring and fall) by the National Science Foundation on behalf of the Interagency Arctic Research Policy Committee and the Arctic Research Commission. Both the Interagency Committee and the Commission were authorized under the Arctic Research and Policy Act of 1984 (PL 98-373) and established by Executive Order 12501 (January 28, 1985). Publication of the journal has been approved by the Office of Management and Budget.

Arctic Research contains

- Reports on current and planned U.S. Government-sponsored research in the Arctic;
- Reports of ARC and IARPC meetings; and
- Summaries of other current and planned Arctic research, including that of the State of Alaska, local governments, the private sector and other nations; and

Arctic Research is aimed at national and international audiences of government officials, scientists, engineers, educators, private and public groups, and residents of the Arctic. The emphasis is on summary and survey articles covering U.S. Government-sponsored or -funded research rather than on technical reports, and the articles are intended to be comprehensible to a nontechnical audience. Although the articles go through the normal editorial process, manuscripts are not refereed for scientific content or merit since the journal is not intended as a means of reporting scientific research. Articles are generally invited and are reviewed by agency staffs and others as appropriate.

As indicated in the U.S. Arctic Research Plan, research is defined differently by different agencies. It may include basic and applied research, monitoring efforts, and other information-gathering activities. The definition of Arctic according to the ARPA is "all United States and foreign territory north of the Arctic Circle and all United States territory north and west of the boundary formed by the Porcupine, Yukon, and Kuskokwim Rivers; all contiguous seas, including the Arctic Ocean and the Beaufort, Bering, and Chukchi Seas; and the Aleutian chain." Areas outside of the boundary are discussed in the journal when considered relevant to the broader scope of Arctic research.

Issues of the journal will report on Arctic topics and activities. Included will be reports of conferences and workshops, university-based research and activities of state and local governments and public, private and resident organizations. Unsolicited nontechnical reports on research and related activities are welcome.

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Cover

Pacific brant at San Quintin Bay, Baja California, Mexico. This sea goose nests in Alaska and winters in California and Mexico. It is the subject of an international cooperative research and conservation effort between the U.S. and Mexico, described on page 25.

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ARCTIC RESEARCH OF THE UNITED STATES

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U.S. International Policy and Scientific Research in the Arctic

This article was prepared by Tracy A. Hall, U.S. Department of State, and Charles E. Myers, National Science Foundation.

In the international arena, U.S. policy in the Arctic has historically focused on scientific research and environmental protection, in addition to defense issues that arose during the Cold War. In 1991 the United States, along with Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden, became signatories to the Arctic Environmental Protection Strategy (AEPS), a high-level forum designed to identify priorities for regional cooperation with regard to environmental protection in the Arctic. Organizations representing the Arctic indigenous communities also were invited to participate in the AEPS.

In September 1996 the eight Arctic countries signed the Declaration on the Establishment of the Arctic Council and expanded the AEPS mandate to deal with issues of sustainable development in the Arctic. The Council, like the AEPS, comprises four subsidiary groups: the Arctic Monitoring and Assessment Program (AMAP); Conservation of Arctic Flora and Fauna (CAFF); Emergency Prevention, Preparedness, and Response (EPPR); and Protection of the Arctic Marine Environment (PAME). Discussions are currently underway to establish a fifth subsidiary group for sustainable development.

On September 18, 1998, at the first ministerial meeting of the Arctic Council, held in Iqaluit, Northwest Territories, Canada, the U.S. formally assumed the role of Chair of the Council. The U.S.'s two-year tenure as Chair will conclude with a U.S.-hosted ministerial meeting in Alaska in the fall of 2000.

As host of the Arctic Council from September 1998 to 2000, the U.S. Department of State would welcome hearing from individuals and agencies with an interest in participating in the work of the Council. Interested individuals are encouraged to visit the Arctic Council web site at <http://arctic-council.usgs. gov>.

During its two-year chairmanship, the U.S. will provide overall leadership for the Council by staffing a secretariat and by ensuring an effective flow of communication among Arctic Council member countries. The U.S. will continue to participate in each of the four subsidiary groups of the Council and will work closely with the State of Alaska to identify and pursue appropriate projects related to sustainable development in the Arctic. Current U.S. projects that have been proposed for acceptance by the Arctic Council sustainable development program include Arctic Cultural and Eco-Tourism, Arctic Telemedicine, and Technology Transfer to Improve Arctic Sanitation Systems. In addition to participating in these programs, the U.S. intends to increase its focus on human health. Human health in the Arctic is currently addressed within the Arctic Council as a component of AMAP. U.S. agencies with interest in this area are discussing whether or not health should be a separate subgroup of the Council and whether the Council should address social as well as environmental issues within this group.

To date, the Arctic Council's subsidiary groups have focused on monitoring the existence of various contaminants in the Arctic, as well as the risks to certain populations of flora and fauna. Future activities within the Council may include discussions of appropriate actions to reduce contaminant levels and mitigate risks. Contaminant monitoring during the second phase of the AMAP program will continue. In addition, discussions are underway to draft an Arctic Council action plan, which would outline steps and priorities to address the pollution threats and problems identified by AMAP.

Scientific research contributes to the knowledge base and data that underlie and inform the Arctic Council's subsidiary groups. This issue of *Arctic Research of the United States* highlights some of these international research projects.

International Programs in the Western Arctic/Bering Sea Region

This report was prepared by Gunter Weller, Professor Emeritus, Geophysical Institute, University of Alaska Fairbanks.

The Western Arctic/Bering Sea region, which is vital to many nations because of its fisheries, oil and gas resources, and Native communities, is becoming the focus of increased international attention and research. Changes in the region during the past few decades have occurred at a rapid pace, with both natural environmental fluctuations and human activities having effects on the Bering Sea ecosystem. Many of the changes have been driven by the substantial climate warming that has taken place, both on land and at sea. Societal impacts will become even more pronounced if present climatic trends continue. Concern about the Bering Sea ecosystem and uncertainties about its future have led to many workshops that involve more than one organization. For example, one held in December 1997 was organized jointly by the U.S. Department of the Interior, the National Oceanic and Atmospheric Administration (NOAA), and the Alaska Department of Fish and Game.

To address some of the concerns raised at these workshops, a number of major research projects will focus on the Western Arctic/Bering Sea region over the next few years. They include studies of marine and terrestrial ecosystems and their transitions as the climate changes, regional feedbacks on the global climate, and present and future environmental and socioeconomic consequences of these changes. Several Federal agencies are playing leading roles in this research, international partners are involved, and the goal of promoting and facilitating research among all organizations active in Western Arctic research is being achieved. The University of Alaska Fairbanks is helping to bring these diverse research efforts together through its Cooperative Institute for Arctic Research.

NOAA ship Miller Freeman *conducting oceanographic research in the Bering Sea as part of a new NOAA Arctic Research Initiative.*

NOAA's Arctic Research Initiative in the Bering Sea

A major new research program in the region, an Arctic Research Initiative called Health of the Bering Sea Ecosystem, was first funded by NOAA in 1997. One of the highlights of this research in 1997 was a major interdisciplinary cruise along the Bering Sea shelf break on the NOAA ship *Miller Freeman*. Seven oceanographic transects were conducted across this highly productive region, labeled the "green belt," collecting data on the Bering Slope Current's location and strength, on photosynthetic activity, and on other oceanographic parameters.

Following 15 initial studies funded in 1997, including the projects on the *Miller Freeman,* 22 research projects will be conducted in 1998. About half of the projects are concerned with the natural variability of the Bering Sea ecosystem and the atmosphere–ice–ocean interactions that control this variability. The other half deal with anthropogenic influences, including atmospheric and marine contaminant studies and their effects on biota and eventually on humans. The four major research thrusts are:

- Processes and ecosystem production in the Bering Sea green belt;
- Atmosphere–ice–ocean processes that influence ecosystem variability;
- Arctic haze, ozone, and UV flux and their potential impacts; and
- Contaminant inputs, fate, and effects on the ecosystem.

With this new funding, NOAA is strengthening U.S. marine ecosystem and meteorological and

For further information on any of these projects managed by the University of Alaska Fairbanks (UAF), consult the following web pages:

NOAA's Arctic Research Initiative: www.cifar.uaf.edu

NSF's LAII-ATLAS research project: www.laii.uaf.edu

Bering Sea Regional Impacts Assessment: www.besis.uaf.edu

International Arctic Research Center: www.iarc.uaf.edu

oceanographic research in the Bering Sea, as well as continuing major contributions to the study of atmospheric pollutants such as Arctic haze. Studies of the green belt, meteorological processes associated with the Aleutian low, and the oceanographic processes in the Bering Strait are emphasized. Interdecadal variations in atmosphere–ice–ocean interactions are beginning to shed new light on climate change. Studies of marine contaminants and their effects (for example, mercury) were begun modestly in 1997 and have been strengthened, and there is a new emphasis on contributions to AMAP, the international Arctic Monitoring and Assessment Program. Also, the studies of contaminant effects are establishing new and much closer links with Native communities and individuals than in the past. The program is managed for NOAA by the Cooperative Institute for Arctic Research (CIFAR) at the University of Alaska Fairbanks.

Arctic Transitions in the Land–Atmosphere System

The second major research program in the region is just beginning in 1998 under the Land–Atmosphere–Ice Interactions (LAII) study of NSF's ARCSS (Arctic System Science) program. It follows an earlier four-year Flux Study that examined carbon dioxide and methane sources and sinks in the Kuparuk River basin of northern Alaska that could have feedback effects on the global climate. The new study, called ATLAS (Arctic Transitions in the Land–Atmosphere System), is examining Arctic land transitions that are caused by climate change. Eight multi-PI cluster projects, ranging from climate to vegetation, trace gas, and hydrology studies, are involved, covering the following research areas:

- Spatial and temporal transitions of climate and ecosystems;
- Carbon and energy fluxes and carbon cycling in Arctic ecosystems;
- Effects of climate–substrate interactions on Arctic vegetation;
- Soil carbon, permafrost, and active layer dynamics; and
- Snow and vegetation.

Investigators from nine universities and five other research institutions are involved.

This tightly integrated program includes field studies, remote sensing, and modeling. The new field studies will take place in a Western Arctic transect from Barrow to Atqasuk and Ivotuk on the North Slope, moving to the Seward Peninsula and eventually to Chukotka, Russia, over a five-year period. The project is managed for NSF by a Science Management Office at the University of Alaska Fairbanks.

The overall goal of ATLAS is to determine the geographical patterns and controls over climate–land surface exchange (mass and energy) and to develop reasonable scenarios of future change in the Arctic system. This objective is significantly broader than the preceding LAII Flux Study on the North Slope of Alaska in several respects:

- It will extrapolate climate, permafrost, vegetation, and fluxes (heat, moisture, and trace gases) at spatial scales ranging from the plot to the circumpolar Arctic.
- It will develop reasonable scenarios of future trajectories of these parameters over the next 10–200 years.
- The guiding motivation of the research is to improve understanding of the coupled nature of the Arctic system.

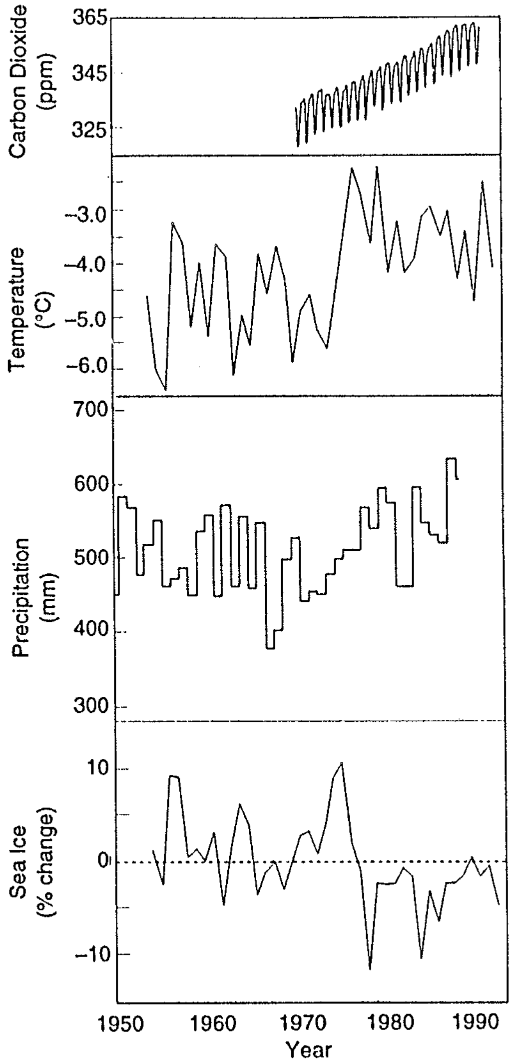
The study will fill a major regional gap in the circumarctic terrestrial network of sites and transects of the International Geosphere–Biosphere Program (IGBP).

Regional impact assessments of global change

The Bering Sea Impacts Study (BESIS) project, initiated by the International Arctic Science Committee and now supported by NSF and DOI through the regional assessment program of the U.S. Global Change Research Program, has begun to synthesize data and information from all regional sources, including the research programs described above. Its goals are to:

- Assess the nature and magnitude of changes in the Western Arctic/Bering Sea region as a consequence of global change;
- Predict and assess the consequences of these changes on the physical, biological, and socioeconomic systems in the region;
- Determine the cumulative impacts of these changes on the region, including assessment of past impacts; and
- Investigate possible policy options to mitigate these cumulative impacts.

The most recent workshop, conducted at the University of Alaska in June 1997, examined and documented climate change in the region and present and future impacts due to climate change on forests, tundra, wildlife and fisheries, the coastal zone, permafrost regimes, social and cul-



Climate change in the Western Arctic. Top: Atmospheric CO_2 at Barrow, Alaska; middle: temperature and precipitation changes in Alaska; bottom: change in sea ice extent in the Bering Sea.

tural systems and lifestyles, resources, and man-made infrastructure. It listed and discussed major impacts already experienced, both positive and negative in relation to human activities, and projected future changes if present climate trends continue. The observed impacts (positive + or negative –) include:

- Major changes in fisheries catches in recent years, due to both longer-term climate change and El Nino conditions (+ and –);
- Accelerated permafrost thawing, leading to costly increases in road damage and road maintenance (–);
- Major landscape changes from forest to bogs, grasslands, and wetland ecosystems due to permafrost thawing, affecting land use (–);
- Increased forest fire frequency and insect outbreaks with lower economic forest yields (–);
- A lengthening of the growing season for agriculture and forestry by up to 20%, producing higher yields (+);
- Increased coastal erosion and inundation, due to less sea ice in the Bering Sea and more severe storm surges, causing threats to structures (–); and
- Impacts on Native subsistence lifestyles as snow and sea ice changes affect land and marine animals used in hunting/fishing (–).

The workshop included representatives from Russia, Japan, Canada, and China. Future annual workshops are planned to update and improve these impact assessments.

A new International Arctic Research Center

An International Arctic Research Center (IARC) has been established on the campus of the University of Alaska Fairbanks to serve as a focal point for Arctic research under the auspices of the governments of the U.S. and Japan. The University of Alaska has agreed to use its existing facilities on the Fairbanks campus, where research institutions, major facilities, and research faculty are located. In addition, to house the new center, a building has been constructed adjacent and connected to the Elvey Building, the home of the Geophysical Institute. Funding for the center is provided by both Japan and the U.S., and it is hoped that it will become a home for Arctic researchers from all countries to participate in the research conducted by the center. Research areas emphasized by IARC will address the global change research programs of both the U.S. and Japan and include numerous topics on climate variability and feedbacks, processes, interactions, impacts, and responses, including:

- Coupled atmosphere–ice–ocean system;
- Dynamic meteorology and radiation;
- Climate variability;
- Hydrological cycle;
- Biogeochemical processes;
- Terrestrial ecosystem;
- Lithosphere;
- Socioeconomic impacts; and
- Middle and upper atmosphere.

The International Arctic Research Center will occupy its new building in early 1999 and will become fully operational at that time.

References

LAII Science Management Office (1997) *Arctic System Science: Land–Atmosphere–Ice Interactions. A Plan for Action.* University of Alaska Fairbanks, 51 p.

The new building for the International Arctic Research Center under construction on the campus of the University of Alaska Fairbanks. The tall structure on the right is the Geophysical Institute, to which the new building is connected.

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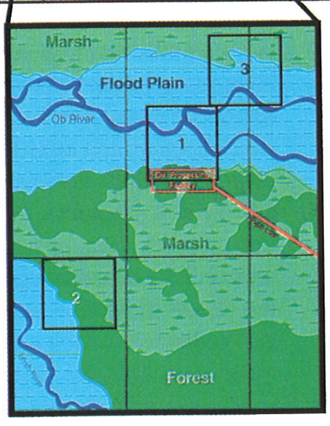
Risk Assessment, Remote Sensing, and GIS in the Russian North

This report was prepared by Peter R. Jutro, Deborah Mangis, and E. Terrence Slonecker of the U.S. Environmental Protection Agency, Brian Orlick of the U.S. National Imagery and Mapping Agency, and Michael True of the Environmental Research Institute of Michigan.

Over the last decade, both sides have come to recognize the enormity of the environmental consequences of the decades of Cold War between the East and the West. The toll was taken largely on Russia and other newly independent states of the former Soviet Union, and each of these countries has been trying to find ways to deal with this legacy.

In the case of Russia, the environmental agenda was high on the list of issues to be dealt with by the binational U.S.–Russian Joint Commission on Economic and Technological Cooperation, formed in 1993, under the leadership of Vice President Albert Gore and Prime Minister Viktor Chernomyrdin. This Gore–Chernomyrdin Commission, or GCC, was created in 1993 to foster expanded cooperation in a range of areas including business development, energy, science, and agriculture, as well as environment. Because of the growing recognition of the relationship between environmental issues and political and economic stability, in 1995 a new Environmental Working Group (EWG) was formed under the GCC to explore the potential for using both countries' classified reconnaissance systems for environmental analysis. The EWG, made up of U.S. and Russian scientists from various government agencies, and representatives of both countries' intelligence communities, worked to evaluate the use of intelligence data for dealing with a range of environmental issues. Among those undertaken were studies on military base cleanup, the status of boreal forests, disaster-related cooperation, the role of the Arctic Ocean on the global climate system, and the risk presented by oil and gas exploration in ecologically fragile Arctic and sub-Arctic regions.

To address the latter, the EWG agreed to select an area that represented both ongoing and planned energy development. The site selected was located in Russia, along the Ob River, near the cities of Neftyugansk and Surgut in the Khanty-Mansiysk region of northern Siberia. Data from both countries' civilian and classified remote sensors were used to create unclassified layers of data for a geographic information system (GIS) database. This GIS was then used to evaluate ecological risk in accordance with a formal, published process for ecological risk assessment developed by the U.S. Environmental Protection Agency.



Location of study sites. The Priobskoye oilfield in western Siberia is a newly discovered deposit located under the ecologically sensitive floodplain of the Ob River. Three study sites were chosen in the study area to assess ecological risk to developed (Site 1), undeveloped (Site 2), and soon-to-be-developed (Site 3) areas.

Background

Intelligence policy

Since the 19th century, overhead imagery has been an integral part of intelligence collection and information policy among the countries of the world. Balloons, aircraft, and eventually satellite platforms have recorded and continue to record a

This work was funded by the U.S. Environmental Protection Agency, through its Office of Research and Development.

scientific treasure of high-spatial-resolution information about the world's surface. Although the immediate information purpose was military intelligence in nature, such as mapping, order of battle, combat readiness, or defensive infrastructure, imagery inherently records data on environmental conditions such as vegetation pattern, extent and distribution of natural resources, topography, and landscape alterations.

However, the relaxation of security constraints on using U.S. classified imagery for environmental purposes has been a long slow process. It began in the 1970s with the removal of some highest-security compartments and recently culminated in Executive Order 12951, in which President Clinton authorized the declassification and release of over 800,000 global satellite images from Corona, Argon, and Lanyard, three former intelligence satellite systems.

GCC

The U.S.–Russian Joint Commission on Economic and Technological Cooperation was established by President Clinton and President Yeltsin during the Vancouver Summit in June 1993. The original emphasis of the commission was to enhance cooperation in the areas of space and energy, but it was quickly expanded to include several other topics, such as defense conversion, health, science, agribusiness, and the environment. The GCC also established two special working groups to investigate 1) the establishment of Russian capital markets and 2) the use of declassified intelligence data for environmental purposes, called the Environmental Working Group.

The EWG agreed in 1995 that one of its primary efforts should be the study of the risks posed by oil and gas development in the fragile Arctic and sub-Arctic ecosystems. These areas are important natural resources for both countries and are under increasing pressure for economic development. Both sides agreed that the specific activities of the oil and gas subgroup should be focused on the information needed to ensure environmental security while exploring economic development.

Specific technological issues are at the heart of the GCC investigations. One of the most fundamental of these is the post-cold-war use of classified remote sensing technology, termed National Security Systems (NSS) data, as one of the primary sources of information for the environmental risk assessment investigation. The remote Arctic and sub-Arctic regions, while rich in natural resources, are areas of sparse population and limited accessibility during much of the year. This limits the availability of other sources of information and makes remotely sensed data a critical information source for collecting landscape information and studying environmental risk. Remotely sensed data, both from open and classified sources, are invaluable (and sometimes the only) sources of landscape history, activity, and morphology.

A second technology theme of the GCC was the requirement to use GIS technology to collect, analyze, and display the data required to study the risks posed by oil and gas development. The risk assessment process inherently requires a significant amount of spatial data concerning the status, extent, and distribution of natural and man-made landscape features. GIS systems provide the tools for storing, retrieving, and analyzing geographic information.

GIS technology is ideally suited to the risk assessment process because it combines the power of computer cartography with the versatility of relational database management systems to create the tools for complex spatial analysis. GIS explicitly encodes the geographic location of environmental, ecological, and anthropogenic features on or near the Earth's surface. For this type of ecological risk assessment, the geographic location of all mapping elements becomes the key to integrating and analyzing all data stored in the GIS system. GIS analysis is based on the fundamental concept of multiple layers of information, each explicitly describing an environmental theme (such as forest cover) in terms of cartographic units (points, lines, and polygons), as well as a potentially infinite number of database attributes, which can be used for geographic and information analysis procedures.

Oil and gas operations

Oil and gas exploration, drilling, production, transportation, refining, and decommissioning all carry significant environmental risks. In Russia, historical practices have led to widespread adverse effects on ecosystems and the broader environment. Exploration activities can include land clearing, with its associated habitat destruction and erosion problems. Drilling, either for exploration or production, poses the threat of groundwater contamination, natural gas leaks, blowouts, and the effects of drilling muds and of cuttings disposal. Production involves the extraction of large quantities of oil, gas, and water. If gas reinjection is not practiced, flaring is common. Untreated water is often contaminated. In the absence of regular maintenance, oil spills from pipelines are to be expected. Modern electronic pipeline monitoring and shut-down capability are not broadly present in the Russian oil transportation infrastructure. Refining involves the generation of many hazardous chemicals, toxic metals, persistent organic pollutants, and toxic particulates. Decommissioning must be undertaken with care, in order to return development sites to a safe, natural state. The Russian oil industry has been working with western oil companies and the Russian government to develop risk-minimizing practices.

GCC EWG oil and gas subgroup

The participants in the oil and gas subgroup of the GCC Environmental Working Group include U.S. and Russian regulatory agencies, intelligence communities, and private industry. Project participants were from:

- The U.S. Environmental Protection Agency (EPA), the U.S. agency charged with protecting human health and the environment;
- The Russian Federal Center for Geoecological Systems, a Russian agency charged with enforcing the environmental laws and suggesting new ones;
- The U.S. intelligence community, which has been monitoring Russian military activity using space imagery since 1960; and
- The Russian intelligence community, which is interested in expanding the use of its domestic imagery for environmental purposes by means of imagery-derived GIS products.

In addition, with the assistance of the U.S. Department of Energy, the group worked cooperatively with two oil companies that held joint leases in the study area: the American firm Amoco and the Russian firm Yukos. Both have a strong interest in maintaining the environmental integrity of their areas of operation.

Study area

The initial study area selected was in the Priobskoye area in western Siberia along the Ob River. This area contains one of the recent discoveries of major oil deposits in Russia and is in the watershed of an important river that flows into the Arctic Ocean. Resource studies have projected that this area could produce over 500 million tons of oil over the next 50 years. An overall study area and three smaller study sites were chosen for GIS database development. These areas were chosen because of their relationship with current and planned oil activities. Site 1 is currently developed and oil drilling is underway. Site 3 is planned for future development, and Site 2 is not being developed and will therefore be used as a control site for evaluation. The leases for these areas are held by Yukos and Amoco.

The entire area is in the channels and floodplains of the Ob and Irtysh Rivers. Seasonal flooding leaves much of the area's morphology characterized by escarpments, oxbow lakes, meandering oxbows, sand dunes, sand bars, shoals, terraced islands, and other typical floodplain structures. Numerous wetlands and lakes of varying sizes are located throughout the floodplain. The area's vegetation is dominated by wetlands and grassy meadow communities, such as sedges and canarygrass. The better-drained areas contain communities of reed grass, cow parsnip, foxtail, and veronica. Mixed tree species grow on the elevated terraces.

Remote sensing data sources

The use of remotely sensed data was critical to the overall project and analytical processes for two primary reasons. First, the combined and peaceful use of a wide range of remote sensing systems was central to the Gore–Chernomyrdin philosophy, and second, the remote location of this area severely limited the availability of other data sets. Civilian and NSS remote sensing systems both contributed critical data to the GIS by identifying and locating the oil infrastructure, outlining water bodies, characterizing vegetation, and delineating wetland and flood boundaries.

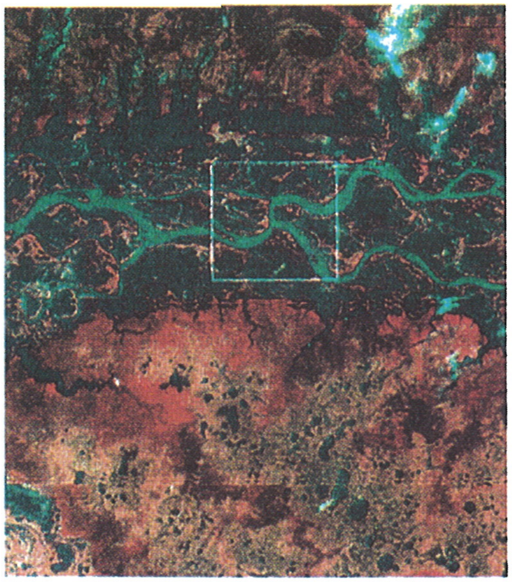
Landsat

Both the Landsat multispectral scanner (MSS) and thematic mapper (TM), with their discrete multispectral bands, were major data sources for GIS development and risk analyses such as change detection. In particular, the Landsat spectral bands allow studies of changes in lake productivity. These lakes and corresponding wetland areas are critical habitats for numerous fish and other species, and their continued health is fundamental to the ecological integrity of this region.

SPOT

The French SPOT satellite provided 10-m-resolution panchromatic data and had sufficient resolution to detect oil production pads and pipelines in the developed regions. This system pro-

Data sources for GIS layers. Data from NSS, civilian satellites, maps, and in-situ measurements were used to create GIS databases at 1:250,000 (overview area) and 1:25,000 (Site 1). Examples shown here include 1) Landsat false color image of the study area during the summer, showing vegetation as red and water as black; 2) close-up of Site 1 in the winter of 1962 from recently declassified imagery of the NSS named Corona; 3) SPOT panchromatic image (1995) of the overview area, showing recent oilfield development; and 4) on-site inspection of an oil storage tank by a joint U.S.–Russian team in 1996.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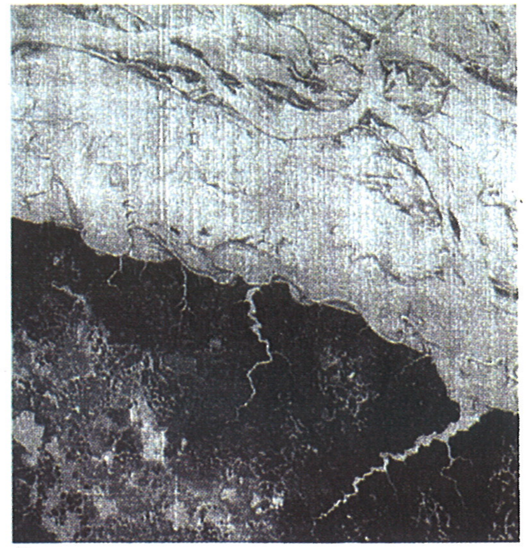
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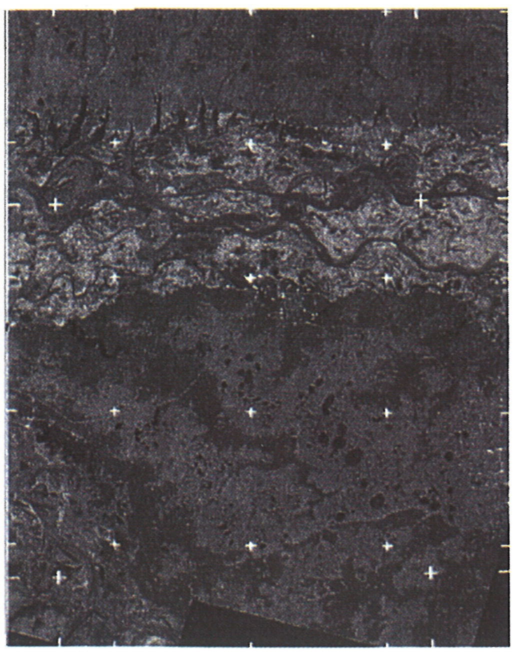
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vided the highest spatial resolution data available from a commercial sensor.

AVHRR

The advanced very high resolution radiometer (AVHRR) has been a constant component of the U.S. NOAA weather satellites. The coverage is daily and the resolution is 1.1 km. The Ob River floodplain is wide enough so that it is resolved on the low-resolution AVHRR images. This sensor is capable of monitoring the ice-blocked northern region of the Ob, which causes the extensive flooding at Priobskoye.

Other civilian sensors

Other civilian remote sensing systems played key roles in this process. The special sensor microwave imager (SSM/I) senses passive microwave radiation emitted from the Earth's surface (that is, brightness temperatures) at four frequencies (19.3, 22.2, 37.0, and 85.5 GHz), with vertical polarization at 22.2 GHz and vertical and horizontal polarizations at the other three frequencies. The spatial resolution of the SSM/I is approximately 25 km at 19.3, 22.2, and 37.0 GHz and 12.5 km at 85.5 GHz. SSM/I allows snow coverage and depth to be monitored on the spatial scale of the entire

Ob River basin. Snow depth is important for some risk assessment algorithms calibrated with in-situ data.

The active microwave, or radar, sensors—ERS-1, JERS-1, and Radarsat—are all-weather systems that can detect spills during the flood season because of the oil-caused damping of wind-generated waves, which changes the radar reflectivity. Active microwave sensors are also used extensively for ice monitoring. ERS-1 data have been used to track the ice floes in Ob Bay. This is important because the time of ice break-up at the mouth of the Ob River determines the flood release in the middle course of the Ob. Flooding has also been tracked on the Ob using ERS-1 data.

National security systems

Vice President Gore and Premier Chernomyrdin agreed, early in the process, that one of the main purposes of the EWG was to examine the use of the national security data acquisition systems of both countries—space-based, airborne, oceanographic, or in situ—and derive unclassified GIS products from its data for environmental use. Because of the remote inland location of the Priobskoye site, imaging sensors (both space-based and airborne) fulfilled the above directive for this project and provided high-spatial-resolution data to complement the spectral (but lower-spatial-resolution) data from the civil sensors.

Other data sources

In addition to remotely sensed and standard GIS data, risk assessments require in-situ and laboratory data in order to adequately describe the stressor, the receptor, and the environment (natural and man-made). In particular, the risk calculation requires the probability of the stressor occurrence (such as a spill), the fate of the stressor (such as petroleum products) in the environment, and the stressor's effect on the receptor. The probability of spill occurrence requires engineering construction data and failure rate data. A number of ancillary data sets were obtained or derived from a variety of sources, such as meteorological and river discharge data from the World Meteorological Organization.

GIS database development

Two general GIS databases were cooperatively compiled by both the U.S. and Russian teams using a variety of remote sensing and existing data sources, including data compiled by Amoco in its oil exploration project. Overcoming technical and scientific language barriers and cartographic and technical differences was the job of U.S./Russian teams of scientists, often working through interpreters. One database was compiled at a 1:250,000 scale for overall analysis, and another was compiled for Site 1 at 1:25,000 scale to show site-specific detail of the oil production infrastructure.

The ecological risk assessment process

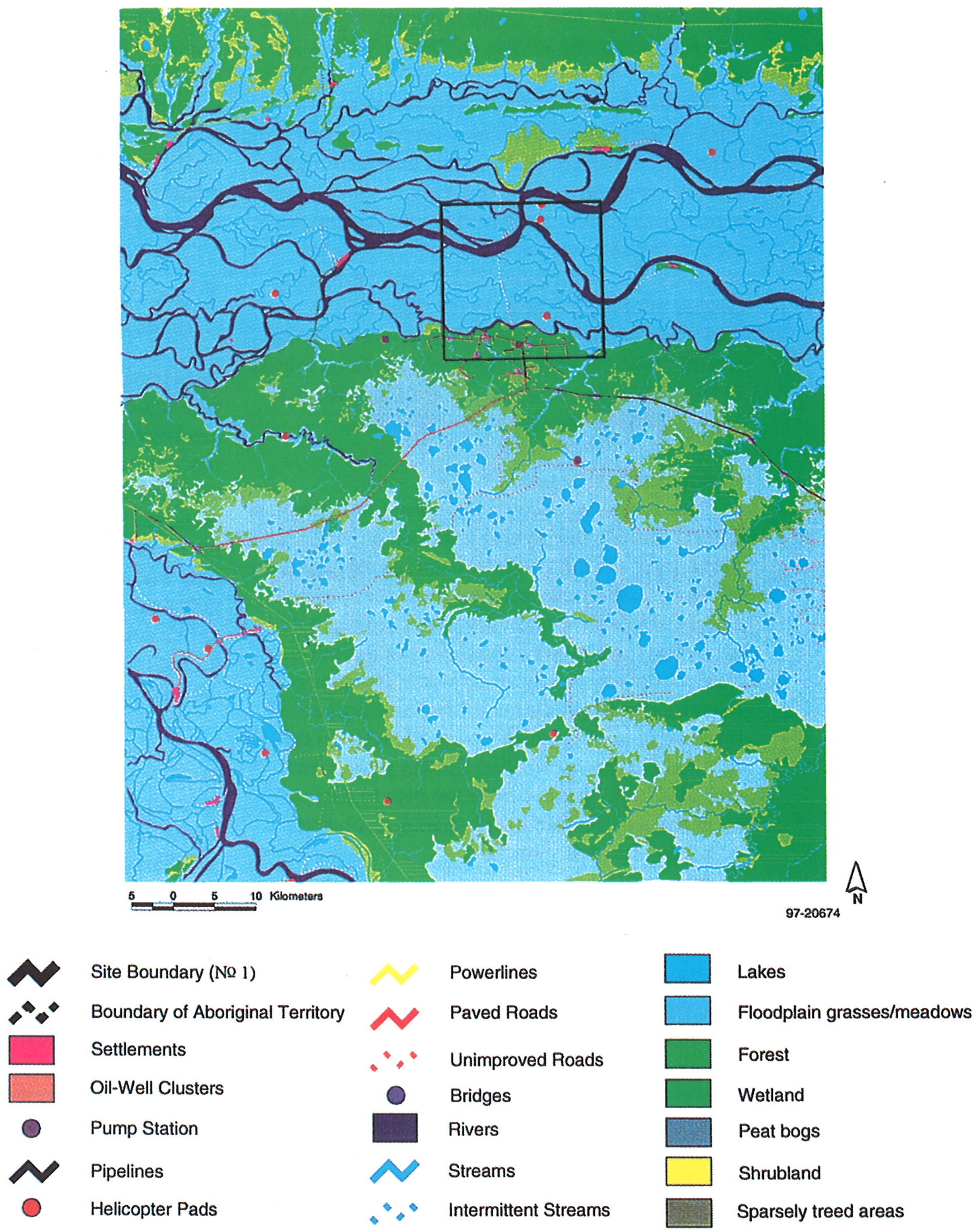
One of the primary goals of the EWG investigation was to develop a methodology for the risk assessment process and to show that this process could be used to make informed decisions about sensitive environments and economically valuable resources. By using GIS technology as a foundation for the risk assessment methodology, managers not only derive greatly improved emergency planning information, but they also gain the tools necessary to balance economic and environmental factors during oil exploration, production, and decommissioning activities.

However, determining ecological risk is a complex process that is based on institutional, legal, and cultural values. During the EWG discussion, U.S. and Russian risk assessment approaches were found to be fundamentally different, requiring the development of a joint risk assessment model.

The Russian approach defines ecological risk as a recognized acceleration of negative processes that could cause disturbance of environmental resilience as a result of anthropogenic impact on the environment. Ecological risk is a comprehensive indicator of potential temporal degradation of ecosystems. Ecological risk can vary based on the nature and viability of management decisions during the planning and implementation phases of economic activities. An ability to alter ecological risk is based on the knowledge of the most significant elements of the environment that are affected by anthropogenic activities and its ecosystem. Ecological risk occurs every time that there is anthropogenic impact on the development of ecosystems. Therefore, the Russian side considers an ecological risk assessment to be an assessment of environmental impact probability attributable to anthropogenic activities. Such a description corresponds with the modern legal and regulatory basis for the environmental laws of the Russian Federation and mechanisms of their implementation.

Russian ecological risk assessment is based on an assessment of environmental resilience in cases

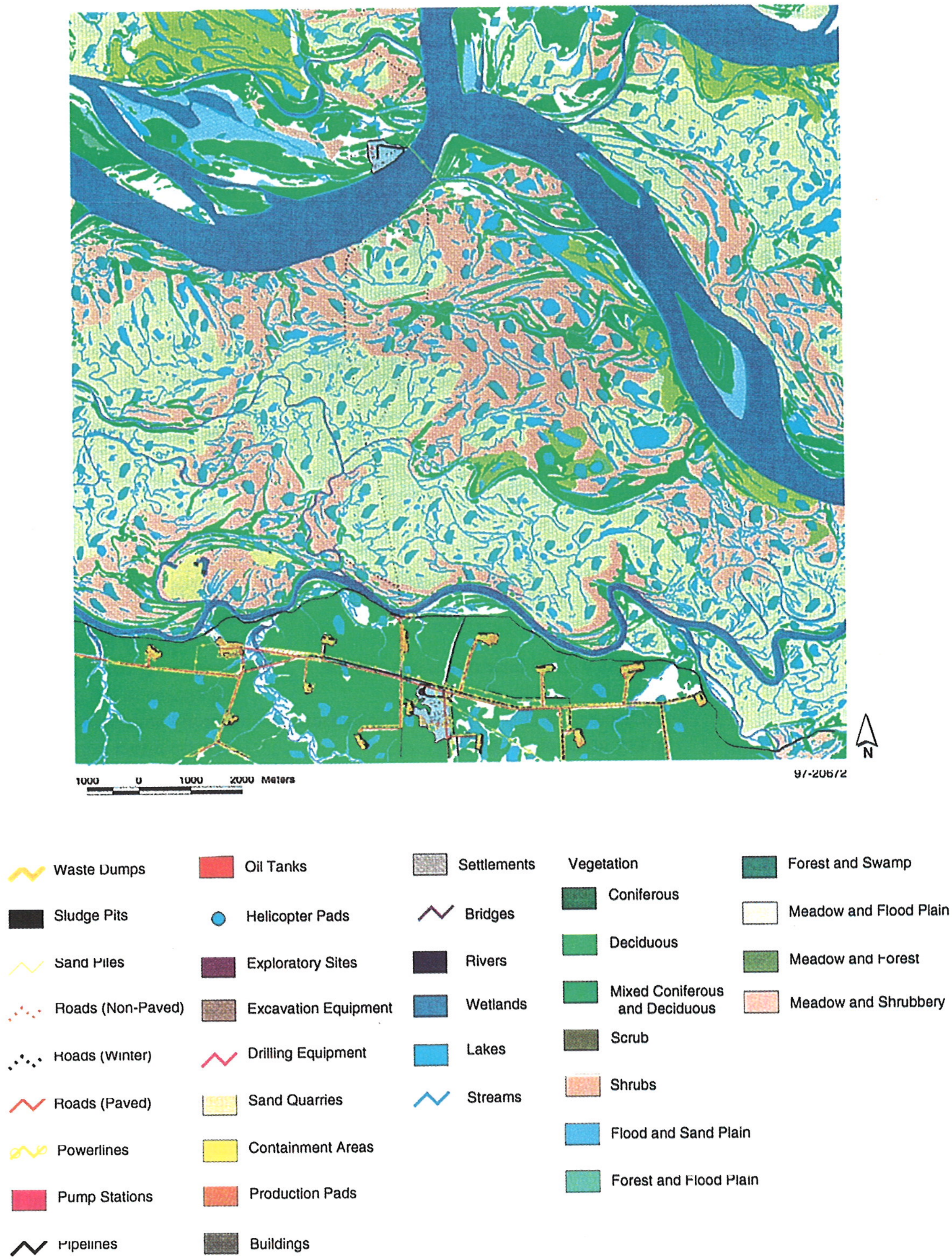
Natural environment and infrastructure layers of the 1:250,000 GIS image of the Priobskoye oilfield. The layers were derived from NSS, civilian satellite, and other data. The Ob River and its floodplain are at the top of the map, and the upland terrace consisting of marsh and forest is at the bottom. In the middle of the map is shown the existing oilfield development on the south (left) bank of the Ob.



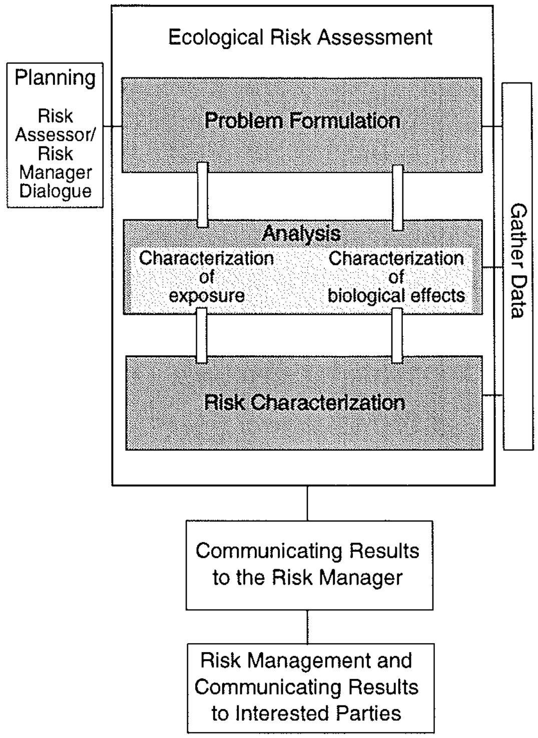
of anthropogenic impact. Resilience is defined as the capability of the environment to recover and clean itself during a stated period of time according to the intensity and temporal parameters of anthropogenic impact. The point of zero tolerance is a level of disturbance beyond which recovery to pre-impact conditions becomes unfeasible. Consequently, high tolerance of the environmental resilience determines low level of risk, and low tolerance determines high level of risk.

In the U.S. methodology, ecological risk assessment, according to EPA guidelines, "evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors." It is a process for organizing and analyzing data, information, assumptions, and uncertainties to evaluate the probability of adverse ecological effects. As discussed in EPA's Ecological Risk Guidelines, an ecological risk assessment consists of the following steps:

Natural environment and infrastructure layers of the 1:25,000 GIS image of the Priobskoye oilfield. The high resolution of NSS data allowed details of the oil pads and pipelines to be included in the GIS. These data are used for risk assessment, emergency equipment placement, and planning of response scenarios in the event of an oil spill.



- Describe the risk assessor/risk manager planning results.
- Develop a conceptual model and the assessment endpoints.
- Review and discuss the major data sources and analytical procedures used.
- Review the stressor-response and exposure profiles.
- Describe the risks to the assessment endpoints, including risk estimates and adversity evaluations.
- Review and summarize major areas of uncer-



Ecological risk assessment. The three primary phases are problem formulation, analysis, and risk characterization.

tainty (as well as their direction) and the approaches used to address them.

—Discuss the degree of scientific consensus in key areas of uncertainty.

—Identify major data gaps and, where appropriate, indicate whether gathering additional data would add significantly to the overall confidence in the assessment results.

—Discuss science policy judgments or default assumptions used to bridge information gaps, and the basis for these assumptions.

Ecological risk assessment includes three primary phases: problem formulation, analysis, and risk characterization. Within problem formulation, important areas include identifying goals and assessment endpoints, preparing the conceptual model, and developing an analysis plan. The analysis phase involves evaluating exposure to stressors and the relationship between stressor levels and ecological effects. In risk characterization, key elements are estimating risk through integration of exposure and stressor-response profiles, describing risk by discussing lines of evidence, determining ecological consequences, and preparing a report. The interface between risk assessors and risk managers at the beginning and end of the risk assessment is critical for ensuring that the results of the assessment can be used to support a management decision.

Problem formulation

Both sides agreed that the overall problem formulation was "to develop the oil and gas reserves of the Priobskoye region in an environmentally and economically sound manner." In meetings with representatives of the oil companies (Yukos and Amoco) and the Russian environmental authorities, the members of the EWG proposed particular issues (including stressors and receptors) that would be addressed in this risk assessment. The group addressed receptors of value (such as upland forest, fisheries, and migratory animals) and stressors of interest (such as oil spills and road construction). Recognizing that it would not be able to address all of the issues, the group chose a subset of stressors and receptors to stimulate further discussion and to illustrate the use of the risk assessment process.

Road construction may affect all of the resources either through direct habitat destruction or through indirect effects such as increased ponding, flood alteration, and the release of sediments into the water. Increased sedimentation may degrade water quality by decreasing the amount of light penetrating the water column, filling the interstitial spaces in the gravel of the stream bottom, or directly smothering fish eggs. These actions may directly affect population levels of fish or may affect the habitat of important food resources. Waterfowl may be impacted indirectly through a reduction of food sources or by impairment of their ability to find food because of increases in turbidity.

Pipeline breaks may release large quantities of oil directly into the water if a break occurs at a stream crossing. If a break occurs on land or in a buried section of pipe, impacts will depend on terrain features and whether or not the released oil reaches the water. There are several ways that waterfowl could be exposed to the spilled oil. The birds may directly contact the spray and ingest oil while preening their feathers to remove it, or they may be impacted by ingesting oil while feeding. The birds may die from direct toxicity of the oil or by the loss of body heat because the feathers lose their insulating property. If the oil spill reaches water bodies, fish may be impacted through direct toxicity of the water-soluble fraction of the oil, by the oil's effect on the respiratory surfaces of their gills, or by a reduction in the availability of food. With respect to water quality, severe impacts often occur when heavy equipment is brought in during the cleanup operations and allowed to operate in the stream channel.

Stressors and receptors chosen for the study

	Valued resources			
Stressor	*Fish*	*Water quality*	*Waterfowl*	*Forest*
Road construction	X	X	X	
Pipeline breaks	X	X	X	
Oil spray		X		X

Oil spray from the production wells and oil/water separators coats the surfaces of trees, inhibiting oxygen transfer and retarding growth. Coating during times of bud or seed production is especially harmful. Oil spray may have direct effects on water quality if the oil enters the water directly or is washed off the land surface into the water.

Analysis phase

The analysis phase, which follows problem formulation, includes two principal activities: characterization of exposure and characterization of ecological effects. The process is flexible, and interaction between the ecological effects and exposure evaluations is recommended. Both activities include an evaluation of available data for scientific credibility and relevance to assessment endpoints and the conceptual model. In exposure characterization, data analyses describe the source(s) of stressors, the distribution of stressors in the environment, and the contact or co-occurrence of stressors with ecological receptors. In ecological effects characterization, data analyses may evaluate stressor-response relationships or evidence that exposure to a stressor causes an observed response.

The products of analysis are summary profiles that describe exposure and the stressor-response relationships. Exposure and stressor-response profiles may be written documents or modules of a larger process model. Alternatively documentation may be deferred until risk characterization. In any case the objective is to ensure that the information needed for risk characterization has been collected and evaluated.

The exposure profile identifies receptors and exposure pathways and describes the intensity and spatial and temporal extent of exposure. The exposure profile also describes the impact of variability and uncertainty on exposure estimates and reaches a conclusion about the likelihood that exposure will occur.

The stressor-response profile may evaluate a single species, populations, general trophic levels, communities, ecosystems, or landscapes—whatever is appropriate for the assessment endpoints. For example, if a single species is affected, effects should represent appropriate parameters such as effects on mortality, growth, and reproduction, whereas at the community level, effects may be summarized in terms of structure or function depending on the assessment endpoint. The stressor-response profile summarizes the nature and intensity of effect(s), the time scale for recovery (where appropriate), causal information linking the stressor with observed effects, and uncertainties associated with the analysis.

Risk characterization phase

Risk characterization is the final phase of an ecological risk assessment. During risk characterization, risks are estimated and interpreted, and the strengths, limitations, assumptions, and major uncertainties are summarized. Risks are estimated by integrating exposure and stressor-response profiles using a wide range of techniques, such as comparisons of point estimates or distributions of exposure and effects data, process models, or empirical approaches such as field observational data.

Risk assessors describe risks by evaluating the evidence supporting or refuting the risk estimate(s) and interpreting the adverse effects on the assessment endpoint. Criteria for evaluating adversity include the nature and intensity of effects, the spatial and temporal scales, and the potential for recovery. Agreement among different lines of evidence of risk increases confidence in the conclusions of a risk assessment.

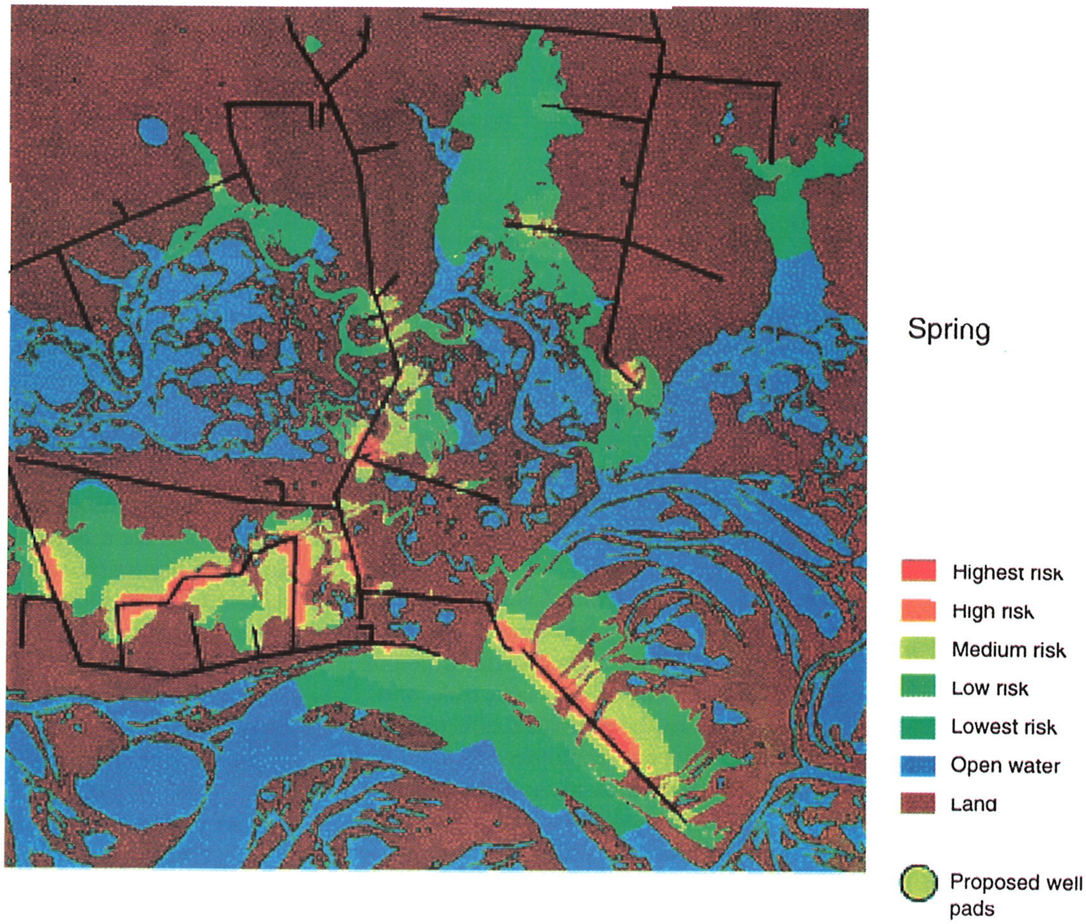
When risk characterization is complete, a report describing the risk assessment can be prepared. The report may be relatively brief or extensive, depending on the nature of the resources available for the assessment and the information required to support a risk management decision.

Analysis and results

Three risk assessment examples, developed using GIS and remote sensing, are described below. Economically valued vegetation, wildlife, and especially food sources of the small indigenous population were prioritized in selecting the examples.

Oil spills

Oil spills are perhaps the most "disaster-like" environmental problem associated with oil production activities. Even with all the safeguards devel-



Impact of an oil spill to lakes, rivers, and streams from all submerged sections of a proposed pipeline route in Site 3 during spring floods.

oped by the regulatory and oil industries, the dynamics of major construction efforts, hostile climate, and water movement create a statistical chance for a spill to occur. It is the purpose of the risk assessment to point out the areas of maximum risk, which can then be reduced by design changes or the siting of cleanup equipment close to high-risk areas.

To properly conduct a risk assessment, the probability of the occurrence of a spill (and the associated spill rate and duration) is needed. This probability distribution depends on many factors, some of which are conditionally dependent on others, such as:

- Construction design (pipeline quality, elevated or buried);
- Adherence to design specifications during construction; and
- Maintenance after pipeline construction.

Given current engineering practices, many factors could affect the probability of a spill. For instance, curved pipe sections or joints are known to fail more often than straight ones. Frost heave can affect buried pipes, and flood or ice scouring are spatially varying physical causes of failure.

When a spill does occur, it has a strong negative impact on the environment, but the degree of the impact is, in part, related to the oil's grade and characteristics. Oil consisting of light hydrocarbons with a short molecular chain evaporates readily and volatilizes quickly, although these oil grades are the most toxic. Heavy hydrocarbons with long molecular chains tend to disseminate slowly and usually settle on soils and the water surface, becoming stagnant for a long time and hampering mitigation efforts. According to our data, oil in the Priobskoye oil field is relatively heavy and dense by conventional standards.

The environmental conditions (including seasonal effects) in a particular area also have a significant impact on the dissemination of oil pollutants. Important parameters required for an assessment of oil spill dissemination include landscape, vegetation, pipeline construction routes, direction and speed of rivers and streams, wind direction, and temperature. In addition, processes such as evaporation, dispersion, and emulsification are important for calculating the time that oil would remain in the environment. Evaporation, the most critical factor in calculating the time and area of oil spill dissemination, depends on temperature; during the summer the volume of oil evaporated would be greater than in the winter.

We analyzed simulated oil spills at three points of existing and proposed pipelines and then extended the point calculations to the entire proposed pipeline. The three oil spill sites correspond to three types of landscape conditions that are present in Site 1 of the Priobskoye oilfield: river, floodplain, and terrace. We considered a hypothetical situation where a pipeline breaks, presumably due to erosion, engineering processes (sagging or heaving), accidental mechanical breaks in airtightness of the pipeline (caused by an off-road vehicle, grader, or icebreaker), or an increase in acceptable pressure levels in the pipeline. The result is an uncontrolled oil spill, with the oil volume hypothetically reaching 500 tons. Oil spill response, containment, and remediation time were not determined. Such a hypothetical oil spill corresponds to a significant accident that would create an emergency situation on the regional level. This hypothetical situation was assessed for three seasons: winter, spring (flooding), and summer (dry). We also analyzed the relative risk to the areas of waterfowl from an oil spill at these three locations. Similar GIS-based analyses were conducted for a variety of environmental receptors under various seasonal conditions.

Road construction

Road construction poses a serious threat to the environment. As a rule, road planning is based on economic effectiveness and safety concerns, including ponding and drainage of terrain on both sides of the road, which leads to infringement on the hydrological and hydrogeological regime of the territory. Another factor is contamination during road construction and operation with construction and general waste and oil products that contain toxic and hazardous materials. Also, consideration must be given to the construction process itself, as it is an infringement on landscape integrity. Finally, there is the problem of new ecological risks that are related to construction of additional engineering facilities along the road, such as power lines and pipelines.

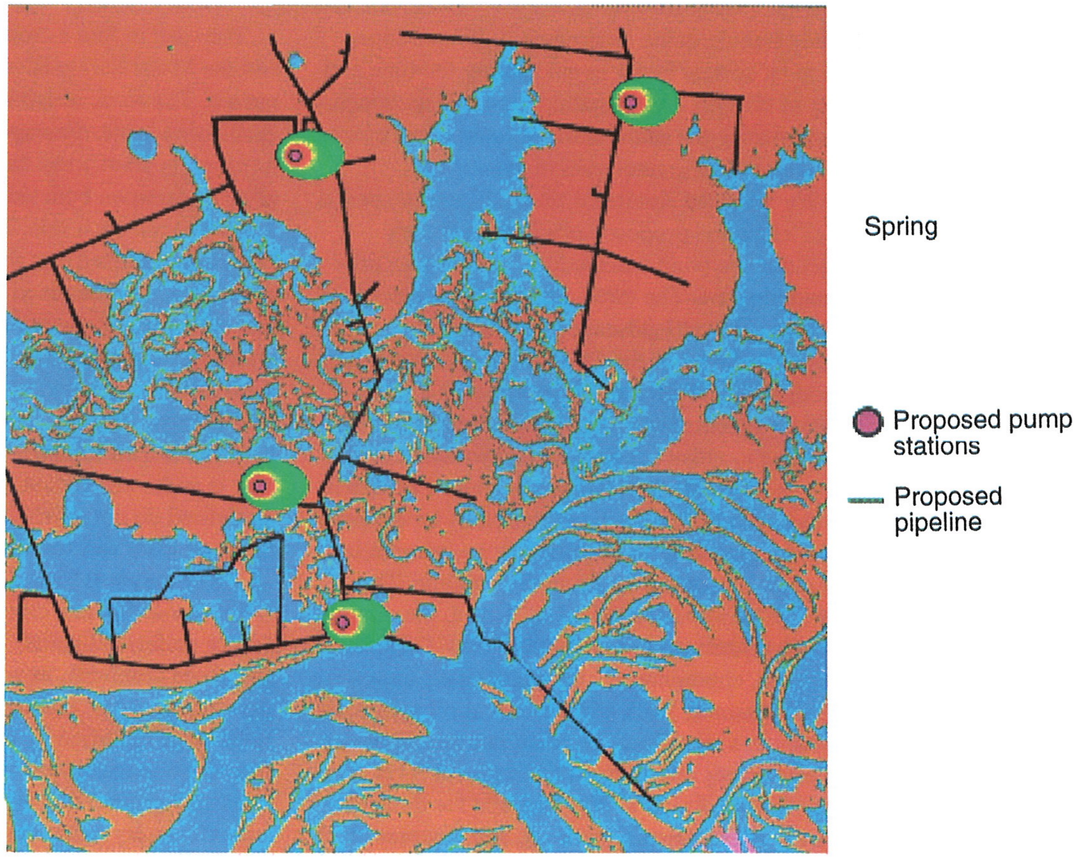
A purely hypothetical road construction was created for study purposes. Although road construction is not planned in this area, such an example provides initial information on the problems that might be avoided or at least minimized.

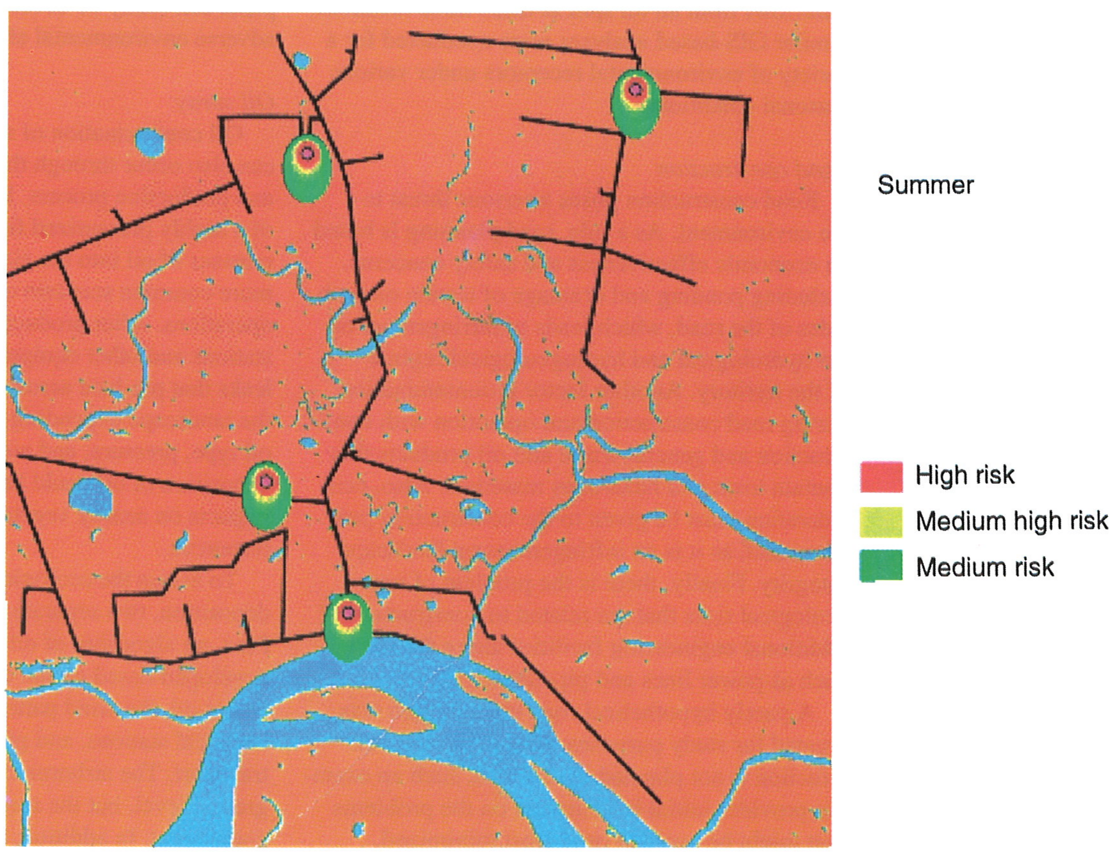
The road in Site 1 crosses the Ob floodplain and the Maliy Salym River and runs through the terrace. The road, which includes road lanes, a cushioning layer, drainage ditches, and adjacent territory, is 50 m wide. In addition, we reviewed affected areas on both sides of the road that are 1 km wide on each side. The majority of birds can be easily dispersed, but the noise pollution would cover large open areas in the floodplain. Forests and tall vegetation serve as noise absorbers, although the road at Site 1 crosses through sections of tall vegetation only after crossing over the Maliy Salym River, where the developed territory begins. As mentioned earlier, the developed territory is under significant anthropogenic impact, so waterfowl do not inhabit these areas. As a result, the ecological risk for waterfowl on the left bank of Maliy Salym is low. The risk increases in the areas where the road crosses sections of the waterfowl's preferred habitat. The simulation showed that these problems, as well as ecological risk in general, would be reduced if the road construction route were modified by introducing additional horizontal drainage systems and diverted to cross over high ground that is less susceptible to drainage effects. By employing classic GIS mapping and optimization techniques, road construction plans can easily be developed that minimize the adverse environmental effects.

Oil spray

Oil contamination of sensitive environments can also occur through the air during the drilling and production process. During drilling, a blowout of a highly pressurized field can lead to large releases of oil into the air and terrain. However, a more common scenario occurs during routine operations. After production begins, the pumping stations and other equipment can produce small leaks that produce aerosols, which deposit oil on the landscape depending on factors such as wind, oil type, pressure, and ambient temperature. This deposition of oil could have significant ecological impacts on nearby vegetation and aquatic resources.

To assess the ecological risks of this oil spray deposition, two separate projects were undertaken. First, an algorithm of oil spray movement was developed based on the characteristics of the native oil, the wind patterns from Russian meteorological stations, and physical models of aerosol transport. The airborne contamination is at nearly ground level, but the spray may have an upward component. In addition, there may be updrafts, *Risk to trees from proposed pump station oil spray in Site 3 during spring and summer.*





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which give another vertical component. Thus, the oil droplets become projectiles influenced by horizontal wind, air drag, and gravity. With a large uncertainty in the oil spray parameters, the extent of the oil spray plume and its resultant damage could include a very large area. However, based on model simulation and GIS analysis, the medium and high risks to forest vegetation were shown to be relatively local to the pumping stations.

Existing research on the impact of light hydrocarbons on photosynthesis and the viability of trees is not comprehensive. It seems that the impact of airborne light hydrocarbons is considerably less than the impact through soils. Moreover, if light hydrocarbons do not cover the ground and are brought into the area by wind, then most likely the concentration of such hydrocarbons is relatively low and would have a harmful effect only on tree stand edges.

In general, then, forests are likely to experience significant disturbance caused by volatile hydrocarbon particles only under conditions of chronic impact. It is likely that high ecological risk would characterize vegetation in the area adjacent to sources of constant pollution, such as pump stations and central oil collection units. Wind direction and speed should also be considered in calculating the area of pollutant dissemination.

A second project was undertaken, using spectral remote sensing data, to determine if there was any impact over time of oil spray deposition on the biological productivity of the many lakes in the Priobskoye area. Multi-spectral remote sensing methods are based on the fact that phytoplankton, containing chlorophyll *a*, strongly absorb energy in the blue and red regions of the electromagnetic spectrum and reflect energy in the green part of the spectrum. By using a basic green–blue band ratio technique, many research applications have successfully correlated in-situ measures of phytoplankton biomass with data from multispectral remote sensing systems. Successful applications have used data from several sensors, including Landsat TM and Landsat MSS. However, these methods rely on simultaneous in-situ phytoplankton measures for calibration. In the Priobskoye study area this type of measurement was not performed at the time of the Landsat TM data collection. Therefore, two other techniques were used to assess potential differences in lake productivity in this area.

The first technique used a simple 2:1 band ratio from 1984 and 1996 Landsat TM scenes that were acquired for this study. Since airborne oil is not likely to travel long distances, it was assumed that oil effects on lakes would be restricted to areas surrounding the specific oil production sites. The TM scenes cover an extensive area of landscape and represent before and after periods of oil production activity in the area. Green–blue band ratios from both the 1984 and 1996 data showed no significant differences in the band ratio signature from any lakes located throughout the TM scenes, except for areas where there was a significant haze problem in the 1984 imagery and one small lake in the southeast part of the scene.

The second method used a change vector analysis (CVA) technique, which is a radiometric change analysis algorithm that uses multiple dates of geometrically registered and radiometrically corrected imagery. CVA uses *n*-dimensional multispectral imagery analysis to produce two fundamental statistics from the radiometric comparison of the multiple date images: change direction and change magnitude. These two statistics, when mapped on a Cartesian coordinate system, essentially reduce multiple bands and multiple dates of imagery into a two-dimensional "change space." This technique includes all multispectral bands in the change determination and can detect changes in both the actual land cover as well as in subtle changes in condition.

This CVA technique was applied to the TM data in the overall region of the oil and gas study. Again, very few significant changes in the lake reflectance were noted throughout the greater oil and gas production area and the overall TM scene in general. One small lake in the extreme eastern section of the study area appears to have been impacted by sedimentation, most likely from adjacent pipeline and/or tank construction activities. This conclusion was based on the observation of new construction in the area and the fact that this was the only lake where any significant change could be detected.

Conclusions

The combined use of GIS and remote sensing technology has utility for international risk assessment. Five key findings are listed in the final EWG report on oil and gas activities:

- High-resolution (1–2 m) remotely sensed imagery is essential for reliable GIS-based environmental risk assessments.
- Historical high-resolution imagery, often available only through National Security Systems, is essential for developing accurate

baseline information on ecological conditions.

- The example risk assessment scenarios showed the dynamic nature and ecological sensitivity of the sub-Arctic ecosystems and thus the importance of conducting ecological risk assessment prior to oil and gas development.
- Cooperative projects, such as the one demonstrated here, between U.S. and Russian government agencies and oil companies will significantly lessen the adverse environmental impact of oil and gas development.
- GIS technology, as demonstrated by this project, is an excellent tool for managing, analyzing, and displaying the data essential to the risk assessment process in fragile Arctic ecosystems. Even when there are significant cultural, legal, and language barriers to the assessment process, GIS technology itself can serve as the language of international ecological risk assessment.

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Sea Ice Classification Using Russian Satellite Data

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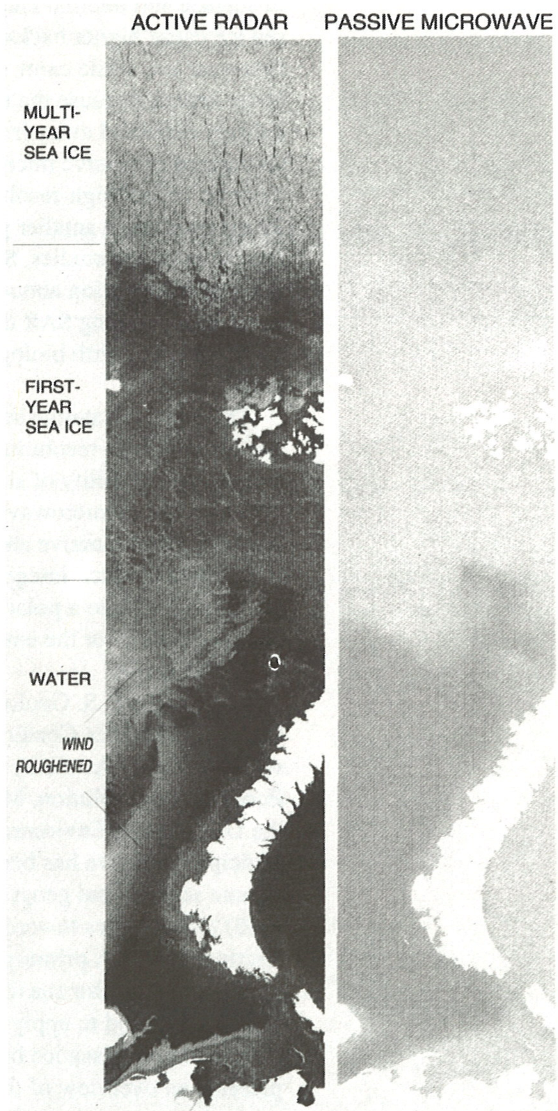
The Arctic ice pack is extremely vast and dynamic, with average seasonal extents ranging from nine million square kilometers in September to sixteen million square kilometers in March. Throughout the annual cycle of winter advance and summer retreat, the structural characteristics and regional distributions of the sea ice are continuously being modified by ocean currents, wind, temperature, and precipitation. This highly dynamic environment is habitat for several marine mammals, including seals, walruses, and polar bears. Information about the relationships between marine mammals and their sea ice habitats is important for assessing a species' biological requirements, predicting effects of habitat changes, justifying protecting key areas, or testing hypotheses concerning underlying ecological processes. However, sea ice habitats are difficult to study because of harsh climatic conditions, inaccessibility, extended winter darkness, and wide-ranging animal movements. Because of the size and movements of the Arctic pack ice, frequent broad-scale studies using aircraft remain prohibitively expensive.

In the early 1970s, satellite remote sensing introduced new technologies for the scientific study of global sea ice. Passive microwave satellite radiometers were launched to measure the amount of radiation emitted by the Earth's surface and atmosphere at predesignated frequencies and polarizations within the microwave spectrum (1–100 Ghz). The amount of radiation a substance emits (at any given frequency) depends on the substance's physical structure, including its electrical properties. Because sea ice has distinctly higher emission properties than ocean water, discriminating signatures, recorded as radiation brightness temperatures, provide a basis for estimating and mapping sea ice concentration.

Microwave brightness temperatures also allow discrimination between multi-year sea ice (ice that has survived at least one summer) and first-year ice, providing a basis for monitoring the distribution of different ice types. The distinction between first-year and multi-year ice is due physical changes in the multi-year ice caused by summer snow melt. Percolating meltwater leaches salinity from the surface ice and leaves behind air pockets that scatter emitted microwaves and reduce the net radiation observed by the satellite. The result is that the brightness temperature over multi-year sea ice is lower than over first-year ice. Global, daily (1978–present), 25-km-resolution, sea ice concentration and ice type data sets (distributed by the National Snow and Ice Data Center, Boulder, Col-



Simultaneously acquired real-aperture side-looking radar and passive microwave images of the Barents Sea region collected by the Russian Okean-07 satellite, 2 January 1997, 16:40 UT.

orado) are a primary source of information for global sea ice and climate modeling studies, but because of their coarse resolution, application to marine mammal studies has been limited to broad-scale investigations.

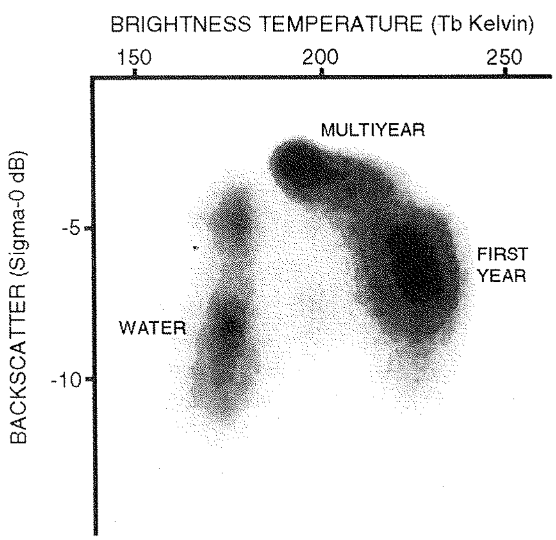
During the recent decade, several synthetic aperture radar (SAR) satellite systems have been launched (Russian Almaz, European ERS, Japanese JERS, and Canadian Radarsat). SAR instruments produce active radar pulses and measure the amount of backscatter energy that is returned from the Earth's surface. Similar to passive microwave radiation, the amount of radar energy returned to the satellite antenna is a function of the electrical and structural properties of the receiving surface. For example, the lower salinity and higher degree of surface and internal incongruities of multi-year sea ice cause higher backscatter return than first-year ice, while calm, open water has even lower return, because the radar pulse is almost entirely deflected away from the satellite origin. Compared to passive microwave systems, SAR systems collect high-resolution data (typically near 20 m) over much smaller geographic areas. For marine mammal studies, SAR data can provide detailed information about local-scale habitat features, but obtaining SAR data that are coincident in space and time with biological sampling can be problematic.

The Russian satellite series Cosmos–Okean carries intermediate-resolution instruments that have the unique capability of simultaneously collecting optical, passive microwave, and active radar data. Acquiring both passive and active information provides more distinct, integrated signatures for sea ice. Launched into a polar orbit, the Okean sensors can record data for the entire Arctic over a three-day period.

In 1990 the U.S. Geological Survey's Alaska Biological Science Center began cooperative work with the Russia Academy of Sciences, Institute of Ecology and Evolution, Moscow, under Area V of the U.S.–Russia Environmental Agreement. Our principal objective has been to exchange and apply remote sensing and geographic information system (GIS) technologies toward contemporary studies of Arctic ecology. A primary focus has been to develop new methods for sea ice mapping using Okean satellite data and to apply the results to studies of marine mammal sea ice habitats. This article presents an overview of the sea ice classification methods that have been developed through our cooperative research. Our study area has focused on the Barents and Kara Seas, where a separate and concurrent U.S.–Russia collaboration has collected two years of polar bear satellite tracking data.

Digital Okean side-looking real aperture radar (RAR) and passive microwave (RM08) imagery of the Barents and Kara Seas was scheduled and acquired through the Scientific Research Center for Natural Resources (Dolgoprudny, Moscow District) from October 1995 through early January 1998. During the study, data were collected by two identical satellite platforms (Okean- 07 and Okean-08). Image acquisition was scheduled to optimally coincide in space and time with the predicted movements of polar bears instrumented with satellite-tracking transmitters. Maximum image resolution was achieved by having all data downlinked to Russian receiving stations using Okean's high transmission frequency (465 vs. 137 MHz). Although the downlink included a simultaneous 960-km-wide swath of 1.5-km-resolution near-infrared imagery (0.8–1.1 μm), these data were typically contaminated by clouds or darkness and were discarded for ice analysis.

Custom software was developed to radiometrically calibrate, equalize, and georeference raw RM08 and RAR imagery. Brightness temperatures were derived for every RM08 pixel based on linear relationships with calibration data that were embedded in the raw imagery during data collection. The radar backscatter coefficient was derived for each RAR pixel as the ratio of the backscatter return power divided by the original output power. Each image was geometrically corrected and



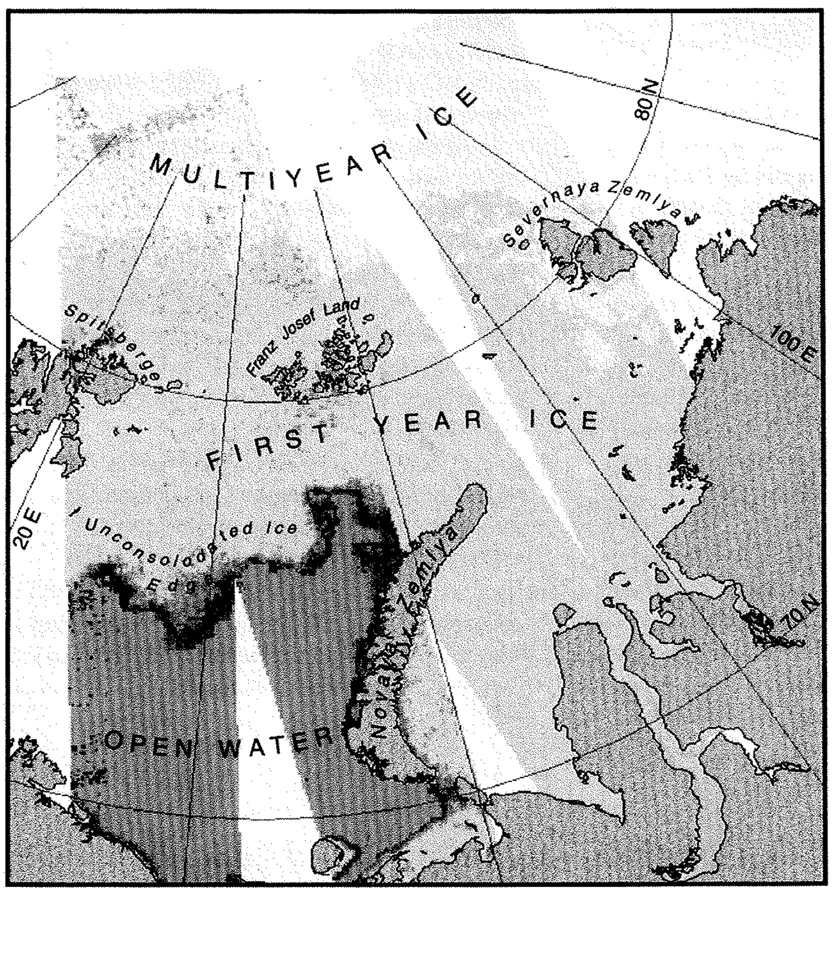
Two-dimensional plot of the same data as in the image shown on p. 21. The three data clusters depict the primary "pure" ice types. The fourth apparent cluster (above the cluster labeled WATER) are pixel values from regions of wind-roughened water.

Okean satellite side-looking real-aperture radar (RAR) and passive microwave (RM08) instrument specifications and raw imagery characteristics.

Parameter	*RAR*	*RM08*
Band	X	Ka
Polarization	VV	H
Wavelength/frequency	3.15 cm/9.52 Ghz	0.8 cm/36.62 GHz
View angle	20–47 degrees	20–50 degrees
Swath width	450–500 km	550 km
Average scene length	3200 km	3200 km
Spatial resolution (range × azimuth)	0.8 × 2.2 km	9.5 × 16 km

equalized to compensate for sensor look angle. The brightness temperature and backscatter coefficient images were converted to ARC/GRID® (Environmental Systems Research Institute, Redlands, CA, USA) format, transformed to polar stereographic projection with 1-km pixel resolution, and averaged to 3-km resolution using a low-pass filter.

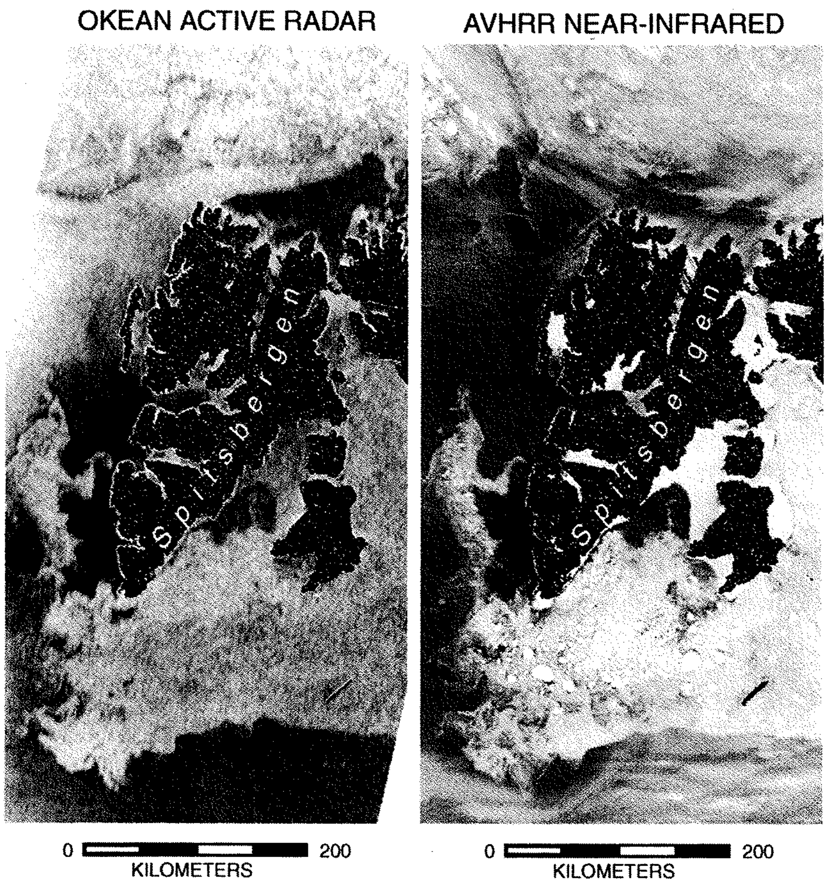
We estimated the concentrations of multi-year sea ice, young or first-year ice, and open water within each pixel using linear mixture models. The ice type coefficients were estimated for each Okean image at the centroids of three data clusters evident on a two-dimensional plot of the brightness temperature and backscatter coefficient pixel values. The three clusters represented the three primary ice types, and their relative positions implied their identification based on published emissivity and backscatter characteristics of the pure ice types. We applied this analysis to each image pixel to create maps of ice type and ice concentration.



Composited sea ice map derived from four Okean satellite scenes, dated (left to right) January 4, 2, 6, 6, 1997.

As with all radar and microwave sea ice classification methods, problems arose when environmental conditions caused confounding between the ice type signatures. When open water surfaces were roughened by the wind, the returned radar backscatter was often sufficient to become confounded with sea ice. Another problem occurred on the pack ice during summer, when the presence of melting snow and surface ponding caused the backscatter and brightness temperature signatures to have waterlike characteristics. Melt conditions typically prevented the discrimination of first-year and multi-year ice types and sometimes led to underestimates of total ice concentration. When necessary, we corrected misclassified ice caused by wind-roughened water by identifying suspect pixels and then substituting an estimate of the open water fraction derived solely from the RM08 microwave data. During summer melt conditions, we estimated total ice concentration without discrimination between multi-year and first-year ice. A third condition that sometimes confounded ice type signatures occurred in areas of highly deformed first-year ice or areas of very young ice, both of which returned sufficient backscatter to suggest a predominance of mult-year ice. For these areas, we used a manually interpreted mask to reassign the multi-year area fractions to the first-year ice class.

The combination of simultaneously acquired passive microwave and active radar data from the Okean satellite provided unique information for developing new methods of meso-scale sea ice classification. Custom software, written at the Russia Academy of Science, represents the only known digital technology for creating georeferenced brightness temperature and backscatter images from Okean data. Although our sea ice classification methodology was not entirely automated, only a modest amount of user intervention was required for each image to control georeferencing, to extract the ice type coefficients, and to visually validate the results. Extracting the ice type coefficients for each Okean image was particularly beneficial for standardizing between-scene



Okean side-looking radar image (10 May, 1997, 02:31 UT) and AVHRR near-infrared (0.73-1.10 µm) image (09 May, 1997, 09:52 UT) of the Spitsbergen region in the Barents Sea. Note the cloud contamination in the upper and lower portions of the AVHRR image and the high backscatter contamination caused by wind-roughened open water in the upper left portion of the radar image.

variability caused by seasonal or diurnal changes in the sea ice properties, as well as any variability within and between the satellite instruments.

The Okean side-looking radar has similar spatial resolution to the advanced very high resolution radiometer (AVHRR), flown on the National Oceanographic and Atmospheric Administration (NOAA) polar-orbiting weather satellites. However, the persistence of clouds and darkness in the polar north preclude applications of AVHRR for systematic sea ice studies. Active radar and passive microwave penetrate through clouds and are not affected by the absence of solar radiation.

The sea ice maps generated by this study will be used to investigate habitat relationships among seasonal distributions of polar bears in the Barents and Kara Seas. Habitat parameters will include ice concentration and ice type, as well as distances to the primary ice edge and indices of habitat diversity. Sea ice habitat conditions will be investigated at weekly locations of 15–20 polar bears tracked by satellite over one- to two-year periods. The results will improve our knowledge about polar bear seasonal habitat use and lend insight into their predator–prey ecology, the implications of global warming, and the design of systematic survey methods for estimating population density.

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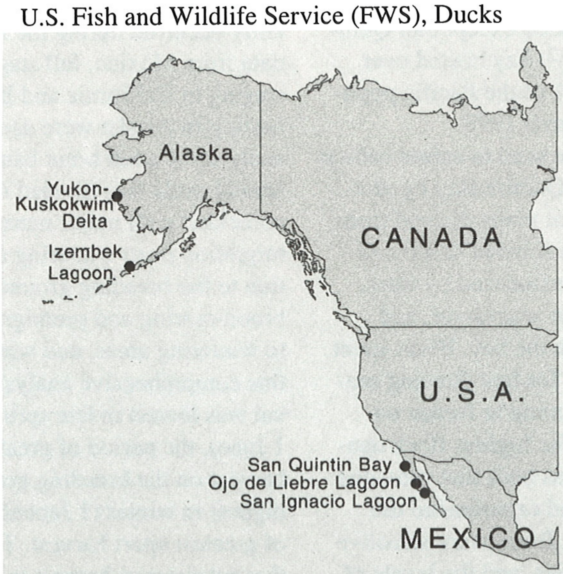
International Cooperative Research to Improve Management of Pacific Brant

This report was prepared by David H. Ward, Alaska Biological Science Center, U.S. Geological Survey.

The Pacific brant is one of three recognized subspecies of brant in the northern hemisphere. Pacific brant nest in coastal habitats throughout northern and western Alaska, northwestern Canada, and northeastern Russia, but most breed on Alaska's Yukon–Kuskokwim Delta (YKD). In fall, nearly the entire population stages at Izembek Lagoon, Alaska, and adjacent areas, before more than 80% make a transoceanic migration to shallow water bays and lagoons of Baja California, Sonora, and Sinaloa. The remaining portion of the wintering population is scattered along the Pacific coast from Alaska to California. Brant are unique among geese because in winter they occur exclusively in marine habitats and feed predominately on seagrasses and algae.

Midwinter counts of Pacific brant have declined since 1961 and recently have approached threshold levels for cessation of sport and subsistence hunting set by the U.S. Fish and Wildlife Service. This downward trend in population size, coupled with increased rates of habitat degradation at wintering areas, prompted joint research between the U.S. and Mexico to identify factors limiting population size and improve management of this sea goose. In 1990 the Alaska Biological Science Center (ABSC), in cooperation with the U.S. Fish and Wildlife Service (FWS), Ducks Unlimited de Mexico (DUMAC) through the Institute of Waterfowl and Wetland Research, and Secretary of the Environment, Natural Resources, and Fisheries of Mexico (SEMARNAP), initiated studies of brant at their primary wintering sites in Baja California, Mexico. These sites included San Quintin Bay, Ojo de Liebre Lagoon, and San Ignacio Lagoon. Research focused on evaluating migration patterns, assessing distribution, estimating annual and seasonal survival, and describing habitat use patterns of brant from different nesting populations.



Major Pacific brant breeding area (Yukon–Kuskokwim Delta), fall/spring staging area (Izembek Lagoon) in Alaska, and wintering sites in Baja California, Mexico.

Winter research in the early 1990s coincided with an extensive marking program on the breeding grounds, which enabled us to determine the breeding origin of birds seen in Mexico. Resightings of marked birds with coded plastic leg bands revealed that Mexico was used by brant from widely separated breeding areas in Alaska, Canada, and Russia. Distribution among wintering sites and timing of arrival in fall were similar for birds from all nesting populations. During spring migration, adults tended to depart northward before juveniles, and adults from sub-Arctic breeding areas left before adults from Arctic breeding areas. Additionally, observations over several winters showed that individuals were faithful to their wintering site and, at a finer scale, to a roosting site within lagoons. Site fidelity can be important to geese because knowledge of local resources and potential risks is believed to enhance survival and reproductive success.

Historically a large proportion of the brant population wintered in coastal areas of California, Oregon, Washington, and British Columbia, but disturbance, habitat loss, and possibly high hunting mortality have greatly reduced the numbers of brant wintering at these sites. Similar disturbance sources and habitat destruction now threaten wintering habitats in Mexico. Recreational activities, salt mining, shellfish farming, and residential development are increasing at all major brant wintering areas.

Detailed research of wintering brant focused on San Quintin Bay, the northernmost area used by

Foraging Pacific brant on a low tide at San Quintin Bay, Baja California, Mexico.

brant in Mexico. Annual FWS censuses of wintering brant showed that San Quintin Bay supported an average of 10–15% of the Pacific population in January 1961–1997. Biweekly ground studies by ABSC and SEMARNAP in 1990–1993 indicated that the bay is also a key staging area during fall (November–December) and spring (March–April). The estimated number of brant using San Quintin Bay represented 30–40% of the Pacific population in fall and 25–35% in spring. The importance of San Quintin Bay to brant was made even more evident during the recent "El Nino" winter of 1997-98, when brant numbers were reduced at all major wintering sites in Mexico except San Quintin Bay. This small (43.5 km^2) bay hosted over 60,000 brant, more than 50% of the Pacific population from December to March 1998.

Ground surveys also were used to assess habitat use patterns of brant in San Quintin Bay by plotting flock locations on habitat maps derived from satellite imagery. These data showed that movements of brant were highly influenced by tides, availability and abundance of seagrasses, and human-caused disturbance in the bay. Brant spent most of their time searching for free-floating seagrass at high tides before moving to forage on exposed beds at low tides. The highest flock densities occurred on the seagrass beds that provided the greatest standing crop and experienced the lowest levels of disturbance. Brant were sensitive to a variety of human activities, and the levels of disturbance at San Quintin Bay were the highest recorded among the lagoons in Baja California. Brant response to stimuli ranged from brief alert behaviors to immediate departure from the site. Disturbances that interrupt foraging time are a concern because they can prevent birds from obtaining necessary resources for migration and egg-laying and thus can lower reproductive performance. Habitat and brant density maps are being used by Mexican government agencies and conservation groups to formulate land use plans for San Quintin Bay.

To better understand when highest adult mortality occurred during the annual cycle, resighting data from Mexico, fall staging in Alaska, spring staging in California and British Columbia, and nesting in Alaska were used in mark–recapture analyses of adult brant banded on the YKD. The annual cycle was divided into six key periods that coincided with major natural events: early spring migration from wintering areas, late spring migration to the breeding grounds, nesting, early fall brood-rearing and premigration, late fall migration to wintering areas, and wintering. The results of this comprehensive analysis indicated that survival was lowest in late spring migration (15 April–1 June), the period of greatest Native subsistence harvest on the breeding grounds, and survival was highest in winter (1 January–1 March), the period of greatest sport harvest. These findings suggested that subsistence harvest in Alaska was the most important factor controlling population size in brant and emphasized the need to develop subsistence harvest regulations and management policies for brant and other waterfowl that nest on the YKD.

Resighting data from Mexico also were used to examine the seasonal and annual survival of first-year brant. Results from this analysis indicated that annual survival was considerably lower (20–30%) for first-year birds than for adults. The mortality of first-year birds was greatest in early fall when birds migrated between the nesting grounds and Izembek Lagoon, their primary fall staging area. Mortality was less likely to occur in late fall, when birds flew from Izembek Lagoon to Mexico. This result is particularly interesting given the relatively short distance (900 km) of the early fall migration and the long distance (5000 km) of the late fall migration. To gain some insight into why mortality was greatest during early fall, we investigated the influence of body mass at the time of banding on first-year survival. Heavier goslings were found to have higher survival rates than lighter goslings, and the effect of body mass on first-year survival was most evident during early fall migration. This suggests that habitat quality, more specifically the ability of an individual to gain weight on the breeding grounds, directly influences first-year survival of brant.

Observations of marked brant in Mexico have also been used to improve estimates of fecundity (that is, age at first breeding) and to test for the effects of handling goslings during banding drives. Currently these data and other demographic parameter estimates are being incorporated into a computer-based simulation model to explore the population dynamics of brant. State and Federal wildlife biologists can use this model to examine harvest strategies and devise management plans that will increase the population size of brant.

The loss of a significant proportion of the remaining habitat in Mexico could be extremely detrimental to brant in the face of the lack of quality wintering areas in the U.S. and Canada. Other subspecies of brant wintering along the east coast of North America and in Europe have switched their reliance on marine habitats to terrestrial ones (for example, agricultural lands). The equivalent adaptation is unlikely to occur in Pacific brant because only arid habitats surround their remaining wintering areas. Therefore, much of the current cooperative research in Mexico focuses on accurately assessing the total extent of intertidal habitats at all major wintering sites for brant. Assessments will be used to develop baseline maps of seagrass distribution and abundance and provide the basis for monitoring long-term change in this critical habitat. Additional cooperative research between the ABSC and botanists of the Center for Scientific Investigation and Education (CICESE) and the University of Northern Baja California will examine the spatial and seasonal variation in the quality and abundance of seagrass to more closely evaluate the effects of winter habitat conditions on movements, survival, and subsequent reproductive success of brant.

The International Tundra Experiment

Understanding Species-Level Responses to Climatic Change in the Circumarctic

This report was prepared by Marilyn D. Walker, Tundra Ecosystem Analysis and Mapping Laboratory, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, 80309-0450. Email: marilyn.walker@colorado.edu

The International Tundra Experiment—ITEX—represents a unique new approach to ecological field experiments. ITEX is a circumpolar network of sites and investigators running a common experiment designed specifically to measure the variability in response of tundra plant species to a realistic level of increased summer warming. This spatially extensive experimental approach is allowing scientists to gather valuable data on how Arctic plant species will respond to global warming.

Global change and scientific inquiry: The need for networks

General circulation models predict that temperature increases in coming decades will be greatest in northern latitudes, as much as 5°C on an annual average basis. Understanding and predicting the responses to these changes in climate require a solid understanding of the patterns and processes operating within the systems, as well as a solid knowledge of the spatial and temporal distributions of these patterns and processes. Understanding of pattern and process can be gained by a combination of approaches that include:

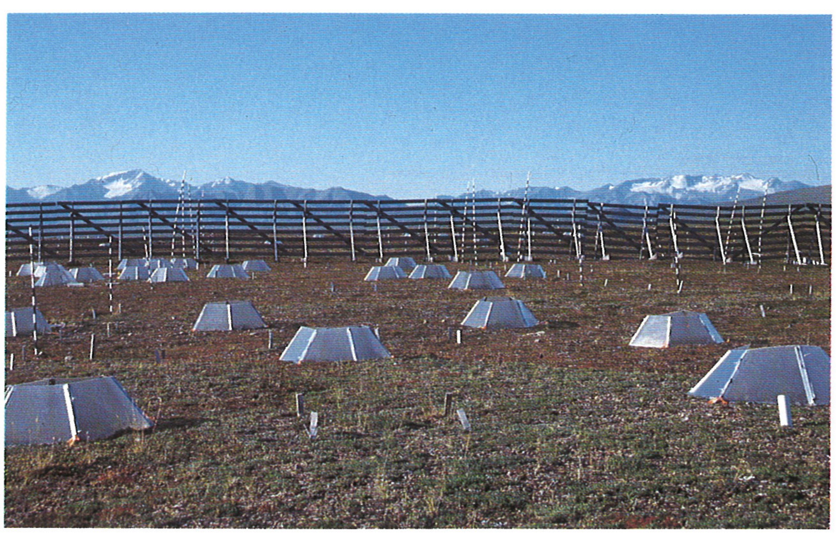
- Monitoring natural systems to have a strong and consistent record of background dynamics;
- Simulation modeling to test both understanding of and potential responses to scenarios; and
- Experiments to understand how and which processes are operating in the system.

Spatial and temporal extrapolation of the understanding gained through these various methods has been approached in many ways: through synthesis of diverse data sets (either informally or quantitatively), through proxy data such as mapping and remote sensing, and through simulation modeling, to name but a few. A problem researchers face in doing these extrapolations is understanding the limits of a particular set of data. For example, a common assumption is that the response of a species to a manipulation or environmental variation can be extrapolated throughout its range. This logical assumption will be true in many cases, but the reality is that we have very little information about or knowledge of the variability in response within species. Another reality is that the great bulk of Arctic research on species has been completed at a few small areas associated with permanent field stations. Comparisons between or among existing sites will inevitably find differences, but with only two or three data points, it is virtually impossible to definitively account for the source of the variation. Comparisons of different substrates at a single site may produce an equally great amount of variability, as will comparisons among sites.

ITEX is unique among scientific networks in at least two ways:

- It is based primarily on an experiment, as opposed to a series of background measurements or common themes; and
- It is a large-scale, Arctic global change program focused specifically on organisms and on organismic responses.

Organismic foci have been conspicuously missing from most global change research, which has focused primarily on the physical system. Ecological global change studies have focused mainly on the carbon cycle, the primary driver of biosphere–atmosphere interactions. The carbon cycle, however, is ultimately constrained by the ability of species to store carbon relative to their nutrient



ITEX installation at Toolik Lake, Alaska, which is also home to the Arctic Long-Term Ecological Research site. Investigators from this ITEX site are studying the simultaneous effects of changes in temperature and snow.

needs, referred to as the carbon:nitrogen, or C:N, ratio. Although species have some ability to change their C:N ratio depending upon environmental conditions, at some point they become saturated with nitrogen and lose their ability to absorb any more. Thus, understanding how the distribution and abundance of species will shift in response to environmental change is critical to understanding the carbon cycle. The ITEX focus on species response therefore represents a critical contribution to global change research.

Common methods: The key to collaboration

ITEX is strongly rooted in common methods, in terms of both manipulations and measurements. The "core" of ITEX is a warming experiment, which was designed by the community in a series of meetings between 1990 and 1992. The ITEX basic experiment is a passive above-ground warming achieved by placing small open-top chambers on the ground throughout the growing season. A set of standardized measurements on a specified set of species assures a common data set among ITEX sites. Defined within ITEX, but not part of the core, are other environmental manipulations such as snow and nutrients, and measurements of ecosystem properties and change such as trace gas flux. Research on the population genetics and heritability of tundra species is also defined as key to ITEX and to our ability to understand and predict species-level responses, but those questions have received far less attention to date.

The ITEX Chambers

The experimental warming required by ITEX is achieved in most cases through the use of small (approximately 1-m-square) chambers. The spatially extensive nature of the experiment required that the chambers:

- Be inexpensive to build and maintain;
- Be lightweight yet structurally strong;
- Have minimal unwanted secondary effects, such as buildup of respiratory and photosynthetic by-products; and
- Not require daily maintenance such as water additions, which are often required for closed chambers.

Design and testing of the ITEX chambers was carried out over several years and involved research teams from the U.S., Canada, Sweden, and Denmark. Chambers were tested in high and low Arctic sites, temperate sites, and Antarctica.

The final design consisted of hexagonal or conical chambers constructed of solar-application fiberglass material, Sun-Lite HP® (Solar Components Corp., Manchester, NH), which transmits 86% of the visible wavelengths and blocks over 95% of transmittance in the infrared wavelengths. In other words, the material allows visible spectra required for photosynthesis and growth to get into the chambers while minimizing heat loss to the outside. The plan was for a design that would result in a 2–5°C warming. The final chamber design increases the mean daily temperatures by 2–5°C under ideal conditions (dry soils, no vegetation, high radiation) and about 1.5–2°C under actual field conditions in most Arctic sites. The open-top design assures that the manipulations receive identical precipitation to controls and prevents accumulation of CO_2 within the chambers. Sites are not required to use the standard chamber design, and some ITEX sites use more conventional greenhouses or small fiberglass "corners," which influence single small populations.

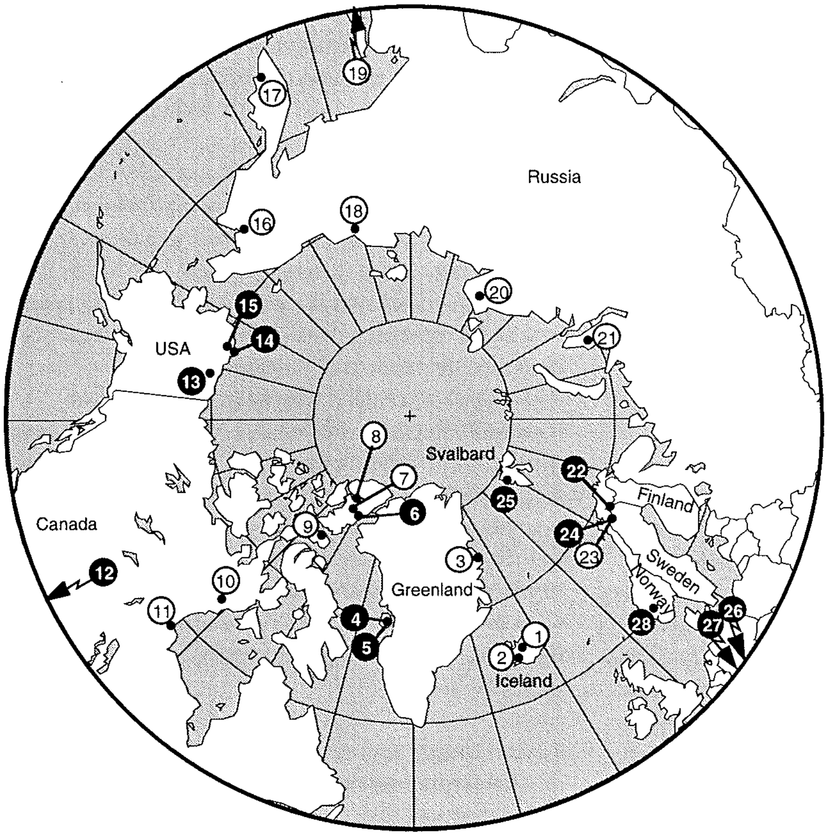
Measurements and manuals

Standard measurements include climate, species abundance and distribution, depth of thaw, and the phenology (the timing of key biological events), reproduction, and growth of a specified set of plant species. A manual describes the experimental and sampling protocols in great detail, including species-specific instructions for measuring phenology, growth, and reproduction. Sampling protocols were taken from other research networks where possible in order to maximize potential collaboration. For example, the climate protocols are identical to those used within the Long-Term Ecological Research (LTER) network, and depth-of-thaw protocols were developed in conjunction with the International Permafrost Association.

The manual is designed to be continually revised and updated as new measurements or protocols are added to the experiment. Each chapter in the manual has been prepared by an individual with direct expertise and experience in that area; if someone wishes to measure a species not described in the original manual, she or he can develop a chapter on those measurements and by doing so assure that their methods will be available to others. A web-based format allows for global access to the most recent version at all times (http://www.dpc.dk/Sites/Secretariats/ITEXManual. html).

ITEX species

A primary goal in designing ITEX was to iden-



1 Audkuluheidi, Iceland
2 Thingvellir, Iceland
3 Zachenberg, Greenland
4 Fortune Bay, Greenland
5 Fjeldspindersletten, Greenland
6 Alexandra Fjord, Canada
7 Sverdrup Pass, Canada
8 Hot Weather Creek, Canada
9 Truelove Lowland, Canada
10 Baker Lake, Canada
11 Churchill, Canada
12 Niwot Ridge, USA
13 Toolik Lake, USA
14 Barrow, USA
15 Atqasuk, USA
16 Anadyr, Russia
17 Petropavlovsk, Russia
18 Lower Kolyma, Russia
19 Taisetsu Mts., Japan
20 Taimyr, Russia
21 Yamal, Russia
22 Kilpisjärvi, Finland
23 Abisko, Sweden
24 Latnjajaure, Sweden
25 Ny-Ålesund, Svalbard
26 Val Bercla, Switzerland
27 Furka Pass, Switzerland
28 Finse, Norway

The ITEX network of sites. Black circles indicate sites that contributed data to the recent synthetic effort; some sites are collecting background (non-experimental) data only.

tify a set of species with widespread distributions and reasonably well-known and simple systematics. The Arctic flora provided the perfect candidate pool for this requirement, as approximately 60–80% of its species are in common throughout the circumarctic, or almost so. Many of the species are also in common with northern hemisphere alpine zones as well.

The ITEX science community identified 20 target species to be the initial focus of the measurements, and most ITEX sites include at least some of these species. Ideally all ITEX sites would include as many of the target species as possible, so that a complete set of comparative data would be available. This ideal is impossible, however, because although at least a few of the species will be present at most all sites, they may not be sufficiently abundant to allow for meaningful manipulation and measurement. This is particularly true of the high Arctic and polar desert sites, which have much smaller floras. Many of the species that are critical dominants in low Arctic sites, such as *Betula nana* (dwarf birch), are near the northern limits of their geographic range at those same low Arctic sites and completely absent from high Arctic sites. Failing to measure these dominant species would be to miss data on those components of the ecosystem most likely to drive community change. Thus, most sites combine a few ITEX species with measurements of local dominants that may not necessarily be "official" ITEX species.

Organization and participation

Project organization

ITEX was organized as a Man and the Biosphere (MAB) program and continues under its auspices, with research funding coming from a wide variety of public and private sources. The program originated at a 1990 workshop at the Kellogg Biological Station in Michigan, organized by Patrick Webber. Subsequent meetings have been held in Oslo, Boulder, St. Petersburg, Ottawa, Copenhagen, and London. Meeting support has been made available through various means and funding organizations in host and attendant countries. A major synthesis was completed during a special workshop in Santa Barbara, CA, funded by the National Center for Ecological Analysis and Synthesis. Program support is handled through a part-time secretariat located at the Danish Polar Center in Copenhagen. The next ITEX meeting is planned at Michigan State University, 5–9 January 1999; a major thrust of the workshop will be development of future plans and directions for ITEX.

ITEX is guided by a scientific steering committee that serves primarily as a mouthpiece for the program and as an organizing body. The committee has broad international representation. A Chair, currently Philip Wookey of Uppsala University, Sweden, serves as a spokesperson and advocate for the program internationally.

International sites

ITEX experiments are now in place at over 20 locations, with some sites approaching their fifth and sixth years of data collection. Sites range from temperate alpine (in the Rocky Mountains of Colorado, the Japanese Alps, the European Alps, and the mountains of southern Norway), to low Arctic, high Arctic, and a scattering of polar desert sites. Every Arctic rim nation is included, with the important exception of Russia. Russian scientists have enthusiastically supported the concept of ITEX and have participated in planning and design, yet logistical and funding problems have to date precluded the installation of a stable ITEX site in Russia. Sites have also recently been added in Antarctica and in the sub-Antarctic islands. Although the southern hemisphere sites will be unable to measure the standard ITEX species, they can still contribute through the collection of other species data, which can be analyzed as functional types. The Antarctic Dry Valleys site is completely devoid of vegetation, but researchers there are collecting information on below-ground ecosystems. The willingness of these sites to participate in ITEX also demonstrates the perceived value of the network to the scientific community.

ITEX in the U.S.

ITEX research in the U.S. (USTEX) is funded primarily through the NSF's Arctic System Science Land–Atmosphere–Ice Interactions program (ARCSS LAII). A set of complementary projects address both the standard ITEX experiment as well as extensions of the basic ITEX. A core set of "standard" ITEX projects are in place at Toolik Lake, Barrow, and Atqasuk, Alaska. Subsidiary projects funded as ITEX contributions include experimental manipulation of snow (both increases and decreases), studies of heritability of traits in key ITEX species, and studies of the functional importance of biodiversity. In addition to these LAII-funded projects, the Niwot Ridge alpine LTER site in Colorado is supporting an ITEX experiment, as is the Antarctic Dry Valleys LTER. The Toolik Lake ITEX studies benefit greatly from their placement at an LTER site because of the other long-term data sets and logistical infrastructure available there.

The USTEX program has strong connections to other LAII and ARCSS projects. The ITEX response data have been used to help build decadal-scale models of vegetation change needed for other ARCSS projects. Studies of the functional significance of biodiversity, ongoing within USTEX, are critical to understanding how the biotic system either constrains or feeds back upon regional land–atmosphere interactions (carbon and nitrogen cycles).

Results

Species response to warming

Two major syntheses of the early ITEX data have been completed: a compendium of papers summarizing initial (first and second year) responses of particular species or at particular sites and a meta-analysis of response data from 13 sites. Henry and Molau, in their introduction to the compendium volume on ITEX, asked two key questions of the ITEX data presented there:

- Are the responses relevant?
- Are there common responses among species and sites?

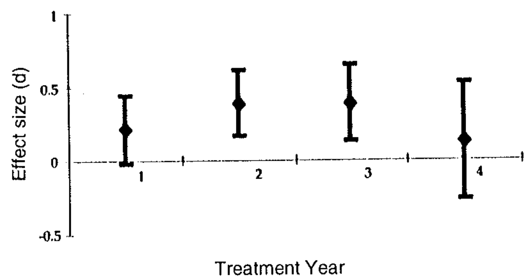
The degree of species response to the low-level warming in the first years has not only been relevant, its magnitude has been somewhat surprising. Thirteen of seventeen species for which responses were reported show detectable to very strong growth responses. Fewer data were available for seed set and germination, but for those species for which data were indeed available, the responses were even more consistent and strong.

Finding trends in complex data sets

Arft and other ITEX researchers used a quantitative, meta-analysis approach to synthesize ITEX response data from 13 sites and 61 species. This larger pool of species allowed them to more carefully examine the patterns of responses within and among the primary functional groups of tundra species. Meta-analysis is an "analysis of the analyses"; it allows results from independent experiments to be pooled into a single analysis to test for overall trends. Just as there will be variation in natural responses across space and time, due to variation in causal factors, there will also be variation in experimental outcomes across studies. Such variation is often reported as "inconsistent responses," usually followed by an attempt to explain the inconsistencies based on ancillary data or expert knowledge. Meta-analysis allows the researcher to systematically test for potential sources of variation within and among different studies, alleviating potential bias in interpretation of inconsistent results.

Meta-analysis allowed the ITEX researchers to search for statistically consistent variation among and within functional groups (that is, forbs, grass-like plants, deciduous shrubs, etc.) and among and within the major climate–environmental systems of high Arctic, low Arctic, and alpine. Analysis of the ITEX data was a new application for meta-analysis, which before that had primarily been

Mean and standard error of "effect size" (Hedge's D), a measurement of the overall experimental effect of the ITEX warming, on vegetative plant growth. "Effect size" is a quantitative expression of the average difference between experimental and control means. An effect of 0.2 is considered small, and one of 0.8 is considered large. Thus, these effects are mainly small to moderate. Because the standard errors in years 1 and 4 overlap 0, they are not considered to be statistically distinguishable from 0, although they remain positive. The strongest effects are in years 2 and 3 of the experiment. Note that years are listed as "Treatment Year" and may represent different calendar years.



used to synthesize and understand bodies of published literature that may appear to show disparate ("inconsistent") results. This was the first known application of the technique to a network experiment, and it is a model for ecological research, not just in the Arctic but in general.

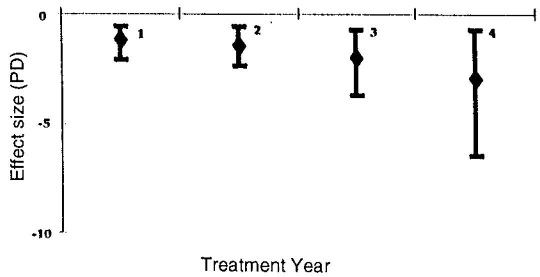
The meta-analysis results indicated some important trends in the data that were not readily apparent from the earlier, more qualitative assessment. Vegetative growth responses were greatest in warmed plots in the first three years of the experiment, but this response shifted to increases in reproductive effort and success in later years. Although more years of data are required to fully understand this shift, it suggests that after three years we are seeing a shift from transient, short-term responses to longer-term responses. This shift is probably caused by a redistribution of the nutrient pools within the ecosystem.

Many of the observed experimental responses are consistent with a nutrient limitation, but in most cases ITEX researchers did not directly measure nutrients. These explanations, therefore, represent only scientific speculation requiring corroboration with data. Warming should cause an initial increase in available nutrients and subsequent uptake of those nutrients by plants and microorganisms, which is then translated into increased growth. The ability of a system to absorb short-term nutrient gains is limited by the biomass available and the efficiency with which the species can take up nitrogen from their environment. Any additional nutrients made available through the warming and not taken up will be quickly lost from the system, limiting long-term response. Chapin and co-workers demonstrated this same principal in their analysis of warmed and fertilized tundra at Toolik Lake, Alaska. In their experiments, warming treatments showed small but significant growth increases over a decade, whereas warmed plots that were also fertilized with additional nitrogen showed much greater increases and much more significant community change. The ITEX meta-analysis confirmed that this pattern holds true for other tundra species and ecosystem types.

Differences in response among functional types and major climate regions (low Arctic, high Arctic, alpine) also support the concept that nutrients ultimately limit response to warming. Significantly greater growth responses were seen in low Arctic as compared to high Arctic sites, although the degree of experimental warming was as high or higher in high Arctic sites. If temperature alone were the main influence on growth, then high Arctic sites could be expected to have some of the greatest responses. This is because the same magnitude of increase in a high Arctic site translates into a much higher percentage increase in thawing degree-days, a more ecologically meaningful measure of biologically available heat. Indeed, one of the initial hypotheses of ITEX was that high Arctic sites should have the greatest responses. But high Arctic tundra, with its lower biomass, also has smaller standing nutrient pools, and thus less nutrients available. Because the high Arctic responses are more constrained by nutrients, they may also be sustained more consistently over the long term than the low Arctic responses, which begin to lag after only three years. Thus, the differences that we see related to spatial pattern may also have a key influence on temporal pattern.

The high Arctic responses may also reflect a different strategy for long-term survival. Although high Arctic sites showed only minimally increased growth, they showed significantly greater investment and success in seed production. These populations have a higher climate-induced mortality rate; a single severe year, even in the midst of a warming climate, may wipe out a local population. In that event, having a store of seed available for recolonization is critical. The genetics work ongoing within ITEX should help decipher some of the differences between environmental limitation and evolutionary constraints related to life history.

Differences among functional types are also apparently nutrient related. The strongest initial responses are in the forbs (herbaceous flowering plants), whereas shrubs, which dominate the low Arctic landscape, had only minimal or no response. Forbs and graminoids (grass-like plants, which include grasses, sedges, and rushes) have a high nutrient uptake efficiency but little long-term storage capacity. Thus, they can quickly take advantage of increased nutrients that become available following a warming. In the longer-term, however, the woody infrastructure of shrubs allows them to continue growth and dominate the



Experimental effect size on timing of leaf bud burst. In this example, effect size (PD) is the simple arithmetic difference between experimental and control means of calendar dates. Thus, the mean difference, although very consistent, is only a few days. The effect is negative because the experimental effect is to have the event occur earlier. The magnitude of the difference is increasingly great over the four years of the experiment, suggesting a potential cumulative effect.

community biomass long after the rich nutrient reserves are used up.

Not surprisingly, another key effect of the warming is to lengthen the growing season by earlier initiation of growth. There was a corresponding extension of the growing season end, but it was significantly different from zero in only one of four years. Thus, the main increase in season length is in the spring. Analysis of the link between timing of growth and amount of growth has not yet been made, but doing so will be important to fully understanding the responses.

Long-term responses: The next phase

Shifts in community composition at decadal time scales have already been observed in the Alaskan Arctic. These responses indicate an increase in shrubbiness in mesic upland tundra, which is consistent with the patterns of vegetation associated with larger-scale climate gradients. We know from the initial phases of ITEX research that there will be a shift from short- to long-term response, and we can make some predictions of what the long-term responses will be based on present species distributions. Yet the nature of transient responses to change will likely be filled with surprises. For example, will there be mechanisms of large-scale mortality for certain species? At the ITEX snow enhancement plots at Toolik Lake, Alaska, for example, we have noted an increase in viral and insect infections of species receiving additional snow. If this trend continues over time, it could greatly speed up the rate at which community change occurs by selectively increasing mortality of certain species. The key to finding "experimental surprises" is in setting up and maintaining the experiments for a sufficient length of time.

ITEX today and tomorrow

The value of the ITEX network and its data have been clearly demonstrated by the high quality of the results and the new information coming from them. Yet the best results have only just begun to appear. ITEX experiments are relatively inexpensive to set up and maintain, and most of the cost is the initial infrastructure. The scientific benefits will increase as we wisely use the infrastructure already in place. The value of the network will be increased by adding new dimensions to the research, but the real pot of gold lies in long-term maintenance of the simple, low-level experiments that were its initial strength.

Participation in ITEX provides both tangible scientific benefits and less tangible, but equally important, professional benefits. ITEX researchers have access to synthesis and workshops and an ability to view their data in new ways. There are also benefits of intellectual interaction with a group of international scientists.

ITEX is also playing an important educational role. A new generation of scientists is already graduating having spent their academic careers in ITEX, and its cooperative approach is their basic research model. ITEX students have opportunities for international travel and collaboration that are often not possible under more traditional research programs. Many of the current leaders in the field of polar biology were trained under the auspices of the International Biological Program Tundra Biome Project; ITEX is a new biologically oriented program that can serve a similar role.

Many potential analyses and studies have been suggested that could be done in association with ITEX sites or as part of the ITEX study. In some cases protocols have been defined for these measurements, but widespread application has not yet occurred. Examples of these include:

- Seed rain and seed bank studies;
- Analysis of vegetation community structure and change;
- Patterns of nutrient and water use;
- Population genetics and heritability;
- Below-ground organisms and below-ground plant parts and phenology;
- Phenology of nutrient use;
- Non-vascular species responses; and
- Species-based modeling.

Any or all of these could be reasonably done within the ITEX framework; the scientific community needs to identify which questions will be most critical to answer in the next phase.

Summary

- ITEX is an international, network experiment focused on organismic responses to environmental warming.

- ITEX is funded in the U.S. as part of the ARCSS LAII program.
- ITEX was designed specifically to be low technology, inexpensive, and relatively easy to set up and maintain.
- Initial results show a strong, three-year transient response period with greatly enhanced growth, followed by a period at reduced response that is likely constrained by total available nutrients.
- Plants growing in high Arctic ecosystems, which likely have stronger nutrient and moisture limitations than low Arctic systems, will show only minor increased growth and will instead produce more seed when experimentally warmed.
- This is a unique new approach and as a scientific model has value to the greater community.

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ARM Climate Change Research in Alaska

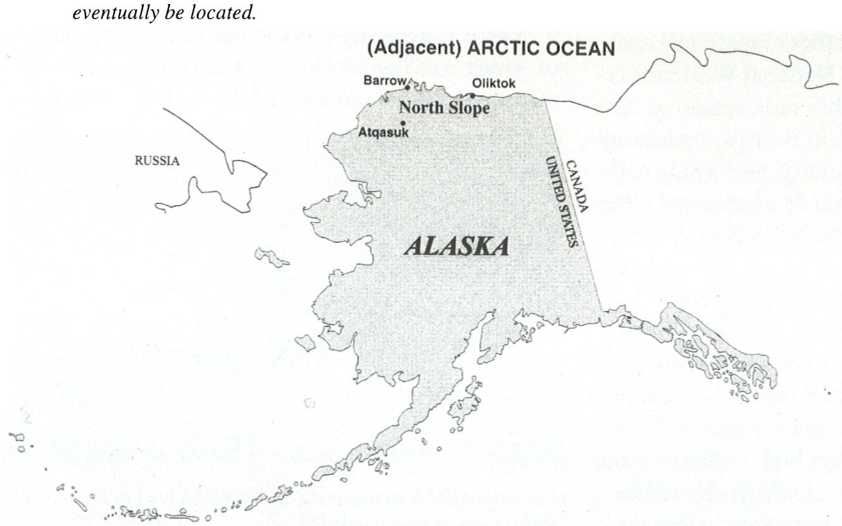
This report was prepared by Bernard D. Zak, Sandia National Laboratories, Albuquerque, New Mexico; Knut H. Stamnes, Geophysical Institute, University of Alaska, Fairbanks, Alaska; and Kevin B. Widener, Pacific Northwest National Laboratory, Richland, Washington.

ARM, the Atmospheric Radiation Measurement program, is the U.S. Department of Energy's principal global climate change research effort. It focuses on radiative energy flows to and from the Earth's surface through the atmosphere, especially in the presence of clouds—which greatly complicate such flows—and on the relevant properties and behavior of clouds. The emphasis is on learning how to better model radiant energy flows in global climate models (GCMs). Detailed understanding of these energy flows is essential to making credible climate predictions.

Barrow site

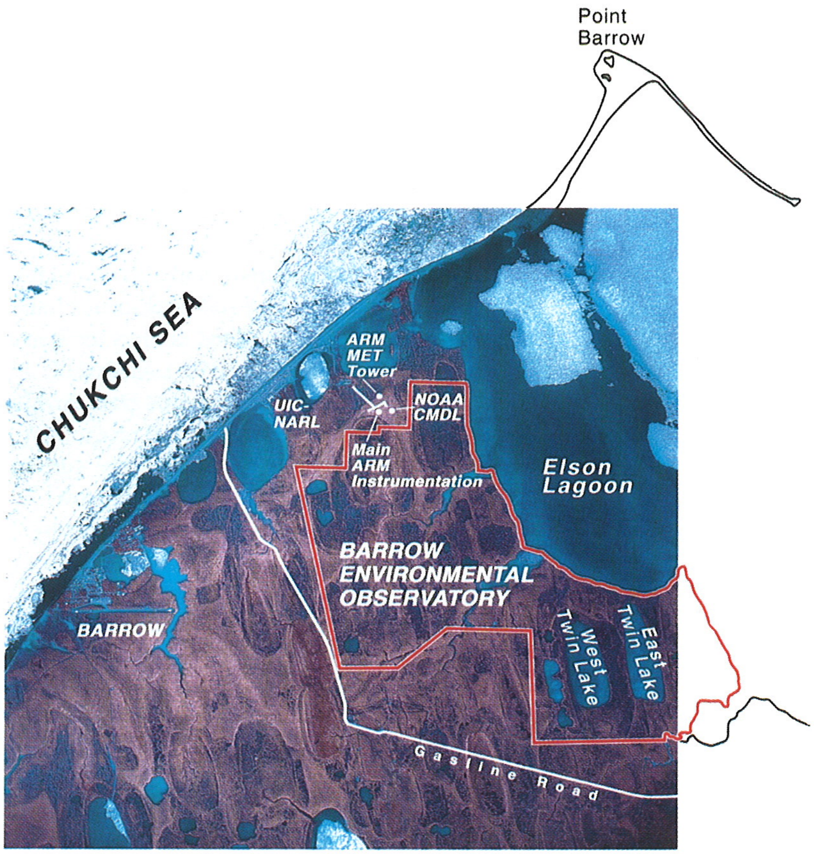
On July 1, 1997, the ARM North Slope of Alaska and Adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) site was dedicated by local North Slope officials and by Martha Krebs, who heads DOE's Office of Energy Research. The NSA/AAO is one of three ARM CART sites around the world. (The other two are in the southern Great Plains of the U.S. and in the Tropical Western Pacific.) The main facility of the NSA/AAO site is located near Barrow, Alaska, and has its sensors on NOAA (National Oceanic and Atmospheric Administration) land adjacent to the NOAA Climate Monitoring and Diagnostics Laboratory station. The NOAA land borders the Barrow Environmental Observatory (BEO), an area of about 25 square kilometers protected from development and set aside for environmental research by UIC (Ukpeagvik Inupiat Corporation), the corporation owned by the Native residents of Barrow. Management of the BEO is supported in part by the National Science Foundation (NSF). Over the past several decades, much high-latitude environmental research has been conducted on this land. ARM's data acquisition system and offices are in the UIC-NARL (former Naval Arctic Research Laboratory) complex about 2 km from the sensors. The basic instrumentation for the Barrow ARM facility was installed during 1997 and early 1998. The CART site began routinely producing data streams in April 1998. The programmatic life of the ARM NSA/AAO CART site is expected to be about 10 years.

Location of the Barrow ARM NSA/AAO facility. Atqasuk and Oliktok are other locations within the ARM NSA/AAO site where additional ARM instrumentation may eventually be located.



The ARM instrumentation at the NSA/AAO site includes both broad-band and spectral radiometric instrumentation covering the near UV (ultraviolet), the visible, and the IR (infrared), that is, both the solar and the thermal segments of the spectrum. The principal spectral instrument acquiring data in the IR is the extended-range atmospheric emitted radiance interferometer (ER-AERI). This instrument covers the IR from below 4 to up to 26 micrometers with one-wave-number resolution. This broad coverage is necessary because in cold regions the concentration of water vapor in the atmosphere is sufficiently low that the longer-wavelength portion of this range (18–26 micrometers) opens up for radiant energy transfer.

In addition, both in-situ and remote sensing instrumentation is in place to document the instantaneous state of the atmosphere above the CART site. This instrumentation includes a micropulse lidar (MPL) for measuring cloud base, cloud, and atmospheric characteristics; a zenith-staring millimeter cloud radar (MMCR) for recording the vertical distribution of clouds even when multiple layers are present; a multi-wavelength whole sky imager (WSI) for documenting cloud coverage and



Aerial view of the Barrow region, showing the locations of the ARM and NOAA instrumentation relative to the BEO and the UIC-(former) Naval Arctic Research Laboratory.

The details of the instrumentation fielded by and relevant to ARM at both SHEBA and Barrow, as well as "Quick Look" data can be viewed at http://kaja.gi.alaska.edu. Data that have been quality assured are available to the general research community through the ARM archive as soon as the quality assurance process has been completed. See the ARM web site at http://www.arm.gov for detailed information on ARM research, sites, and instrumentation. Links exist there to the SHEBA, FIRE, and related web sites.

type; and a dual-channel microwave radiometer (MWR) for measuring the integrated column water vapor and liquid water over the site. A 40-m meteorological tower provides data on the near-surface environment, where strong temperature inversions are frequently found in the Arctic. NOAA CMDL also makes continuous and episodic measurements of the gaseous composition of the atmosphere (which is a source of concern regarding global climate change) as well as of other climate-relevant parameters. In addition, the National Weather Service (NWS) routinely launches radiosondes at its Upper Air Sounding Station in Barrow, measuring profiles of temperature, humidity, and winds with altitude. The NWS sondes can be augmented either at the ARM site itself or at the NWS Barrow Station a few miles away.

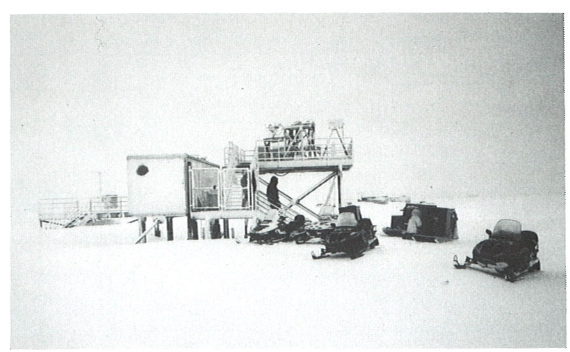
The NSA/AAO CART site is ARM's cold regions climate research facility. In cold regions, water vapor concentrations in the atmosphere are very low, and condensed water typically occurs not as liquid but as solid (ice crystals or snow). These two facts fundamentally affect both radiative transfer and cloud behavior, both of which are within ARM's purview. It has long been known that the interplay of snow cover (which reflects much of the incoming solar energy) and surface temperature (which determines if the snow melts away or not) gives rise to several climate feedback mechanisms that together make high-latitude regions particularly important to global climate.

But cold regions occur not only at high latitudes but at high altitudes as well, not just on mountaintops but high in the atmosphere over the entire surface of the earth. Thus cold regions phenomena are operative over the entire globe, not just at high latitudes. However, relatively little is known of radiative transfer and cloud processes under cold conditions because the regions where they occur—high latitudes and high altitudes—are difficult to access. The ARM NSA/AAO CART site ameliorates this difficulty.

ARM participation in SHEBA

SHEBA, which stands for Surface Heat Budget of the Arctic (Ocean), was an experiment supported principally by NSF's Arctic System Science (ARCSS) program and the Office of Naval Research, with other elements of NSF and other agencies participating as well. The SHEBA experiment involved instrumenting a region of the Arctic ice pack and collecting data on that region through one full year as it drifted with the pack ice. The instrumentation was designed to better quantify the energy flows between the ice and water at the surface and the atmosphere above, as well as the ocean below. The objective is to learn how to incorporate Arctic climate processes in GCMs more accurately. The underlying question that SHEBA addressed was how the Arctic ice pack will respond to the ongoing and projected global warming.

There were many participants in SHEBA, one of which was the ARM NSA/AAO effort. ARM measured the components of the radiative energy



The main ARM instrument shelter on NOAA land as the instrumentation was being installed.

Aerial view of the Canadian icebreaker Des Groseilliers *with the SHEBA encampment growing around it shortly after it was moored to the ice.*

ARM is supported by the Environmental Sciences Division of DOE's Office of Energy Research. ARM is a part of the U.S. Global Change Research Program. The ARM NSA/AAO effort is also part of the Arctic Climate System (ACSYS) program fostered by the International Arctic Science Committee (IASC). Many of the DOE laboratories, including Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories, contribute importantly to ARM in general and to the NSA/AAO CART site effort in particular. The ARM program is administered for DOE by Pacific Northwest National Laboratory. Several academic institutions participate as well, the most notable for the NSA/AAO being the Geophysical Institute at the University of Alaska Fairbanks. In addition, private and governmental organizations in the area play pivotal roles, here especially UIC, the Barrow Arctic Science Consortium, and the North Slope Borough. Other agencies heavily involved include NSF, NOAA, NASA, and NWS.

balance at SHEBA with instrumentation similar to that at Barrow. After being cold-tested at Barrow during the winter of 1996-97, the ARM instrumentation was deployed at SHEBA the following fall. The SHEBA site was centered on the Canadian Coast Guard icebreaker *Des Groseilliers* frozen into and drifting with the Arctic ice pack beginning October 2, 1997. A suitable ice floe to serve as the focus of SHEBA was found in the vicinity of 75°N and 143°W, and the *Des Groseilliers* was moored within it. This initial location was about 500 km north of Prudhoe Bay, Alaska. The floe has subsequently drifted primarily west and then north, ending at about 80°N and 166°W.

ARM participation in FIRE

FIRE (First ISCCP Regional Experiment; ISCCP: International Satellite Cloud Climatology Project) Arctic Cloud is a NASA (National Aeronautics and Space Administration) project coordinated with both SHEBA and ARM that focuses on in-situ measurements aloft using instrumented aircraft. During the spring and summer of 1998 a succession of FIRE aircraft made measurements over both SHEBA and the ARM site at Barrow. The Atmospheric Environment Service of Canada Convair 580 was the first to arrive on the scene in early April. It was followed by the University of Washington Convair 580 and the NASA ER-2 high-altitude aircraft. Later, the NSF's C130 came. Each aircraft is differently equipped and undertook different missions. Some had multi-agency support.

Unlike the other aircraft the University of Washington plane was based at Barrow. Consequently it was ideally positioned to acquire data over the Barrow ARM site. It flew 23 research flights between mid-May and the end of June. Of these, 10 focused on the Barrow ARM site. Most of the other flights focused on SHEBA.

Simultaneous data acquisition of atmospheric characteristic profiles by surface-based remote sensing techniques and by in-situ aircraft within the same atmospheric column is essential for validating both surface and satellite-based remote sensors. For this reason, NASA looks to the ARM sites for much of the validation data for its remote sensing satellites. In the FIRE Arctic Cloud experiment, many of the University of Washington flights were also coordinated with high-altitude overflights by the ER-2, which carried downward-looking remote sensors, essentially emulating a satellite. Satellite data as such were brought to bear as well.

Early results

Although much of the data from ARM, SHEBA, and FIRE have not yet been fully processed and analyzed, certain observations already stand out. The models developed over the past several decades for radiative transfer in the 18- to 26-micrometer portion of the infrared spectrum—a part of the spectrum particularly important for cold regions—represent the data poorly. Modifications have already been made to those models based on ARM NSA/AAO early results and have been incorporated into GCMs. In connection with SHEBA, it was found that the surface layer of the Arctic Ocean is significantly warmer and less saline than had been observed in the AIDJEX experiment two decades ago, and to no one's surprise, the Arctic ice pack is considerably thinner and covers a smaller area.

Looking ahead

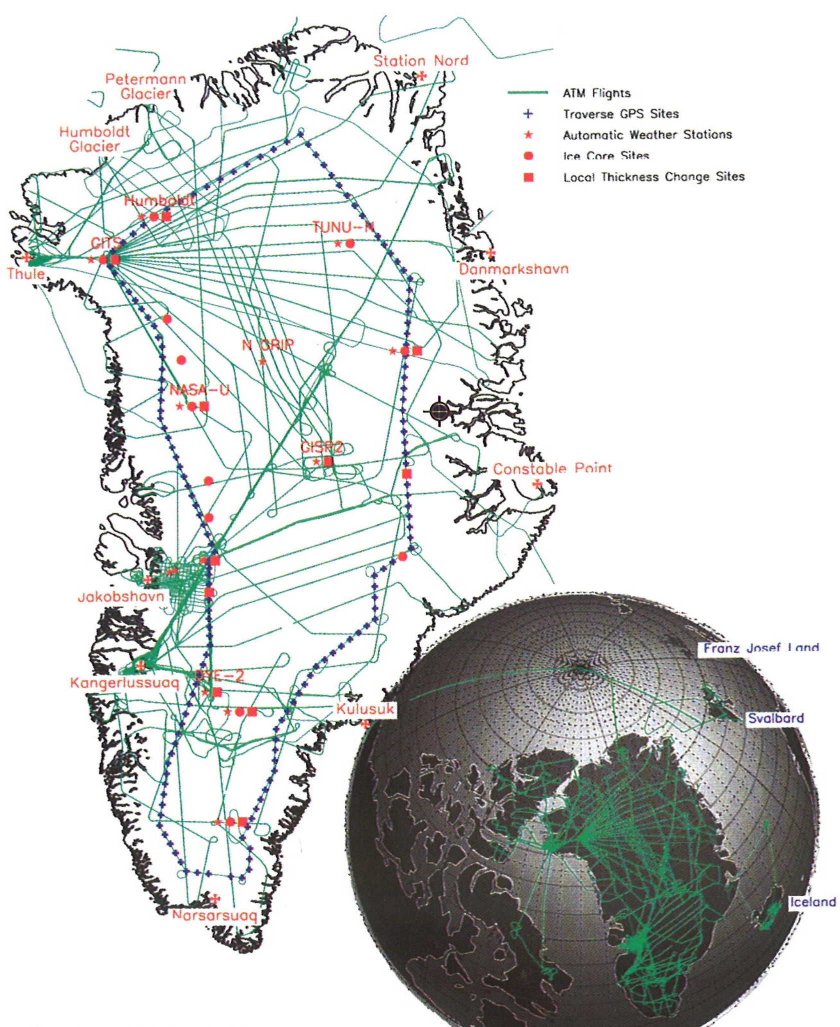
These and the flood of results yet to be realized will take years to be completely digested by the climate research community. But we're off to an exciting start. It is our anticipation that the "The Year of the Arctic" represented by SHEBA, the ARM NSA/AAO CART site, and FIRE Arctic Cloud, will probably raise as many questions as it provides answers. That's the nature of research. As those questions arise, however, the ARM NSA/AAO site and its associated facilities will be in place to help future researchers answer them.

Program for Arctic Regional Climate Assessment

Investigations of the Climate and State of Balance of the Greenland Ice Sheet

This report was prepared by Waleed Abdalati, NASA Goddard Space Flight Center, Greenbelt, Maryland; Roger C. Bales, Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona; and Robert H. Thomas, EG&G Services, Gaithersburg, Maryland.

The Greenland ice sheet spans an area of 1.75 million square kilometers, nearly a quarter of the area of the continental U.S., and with a volume of 2.65 million cubic kilometers, it contains enough water to raise the current sea level by 7 m. In addition, because of its high albedo and large size, the ice sheet plays an important role in the Arctic climate system, acting as a barrier to large-scale circulation. Its moisture, energy, and momentum exchanges with the atmosphere also have a large effect on climate. Despite its importance in the climate system, information on its current state of mass balance, as well as its behavior in a changing climate, is limited. To address these issues, NASA established the Program for Arctic Regional Climate Assessment (PARCA).

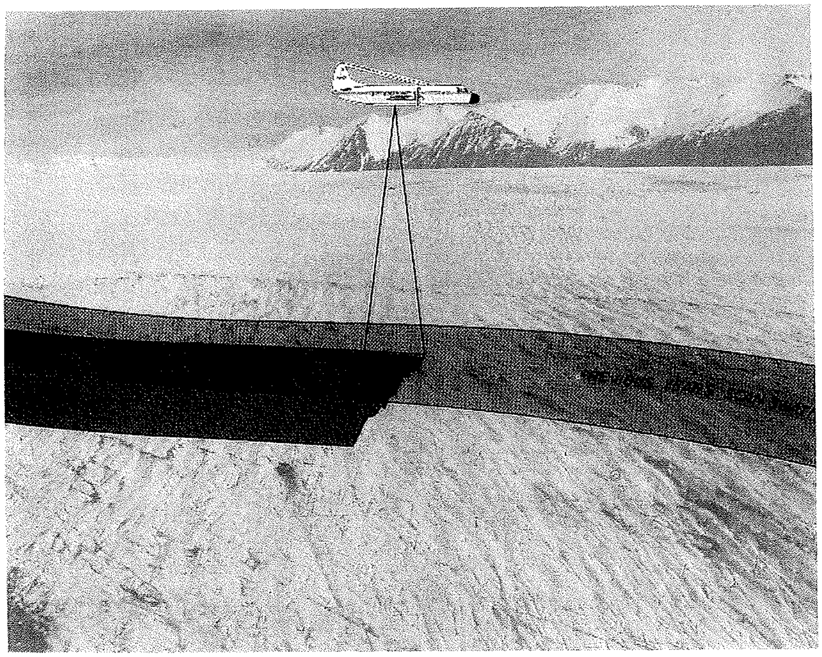


Locations of field activities on the Greenland ice sheet.

PARCA was formally initiated in 1995 by combining into one coordinated program various investigations associated with efforts, started in 1991, to assess whether airborne laser altimetry could be applied to measure ice sheet thickness changes. It has the prime goal of measuring and understanding the mass balance of the Greenland ice sheet, with a view to assessing its present and possible future impact on sea level. In addition to providing valuable information on the ice sheet's physical processes and climate interaction, lessons learned from this program will be applied to the more global assessment of ice sheet volume that will become possible after the 2001 launch of NASA's Geoscience Laser Altimeter System (GLAS), which has the primary objective of measuring changes in ice sheet elevation at latitudes up to 86°N.

The main components of PARCA are as follows:

- Airborne laser altimetry surveys along precise repeated tracks across all major ice drainage basins, in order to measure changes in ice surface elevation;
- Ice thickness measurements along the same flight lines;
- Shallow ice cores at many locations to infer snow accumulation rates and their interannual variability, recent climate history, and atmospheric chemistry;
- Estimates of snow accumulation rates by climate model analyses of column water vapor obtained from radiosondes, satellite atmospheric sounding observations, and European Center for Medium-Range Weather Forecasting (ECMWF) model data;
- Surface-based measurements of ice motion at 30-km intervals approximately along the 2000-m contour completely around the ice sheet, in order to calculate the total ice dis-



The NASA P-3 aircraft, which operates with an accurate on-board GPS navigation system, allowing it to repeat flights of a particular flight line to within 30–50 m. This provides significant overlap of the scanner swaths for the different flights. (Reprinted with permission from Taylor and Francis Publishing Company.)

charge for comparison with total snow accumulation and thus to infer the mass balance of most of the ice sheet;

- Local measurements of ice thickness changes in shallow drill holes;
- Investigations of individual glaciers and ice streams responsible for much of the outflow from the ice sheet;
- Monitoring of surface characteristics of the ice sheet using satellite radar altimetry, synthetic aperture radar (SAR), passive-microwave, scatterometer, and visible and infrared data;
- Investigations of the surface energy balance and factors affecting snow accumulation and surface ablation; and
- Continuous monitoring of crustal motion using global positioning system (GPS) receivers at coastal sites.

An important complement to the PARCA research in Greenland is analysis of ice cores from Franz Josef Land, which aids in understanding Arctic climate variability and changes in sea ice.

Airborne laser altimeter monitoring of the ice sheet

Each year since 1991 the NASA P-3 aircraft, equipped with dual-frequency carrier-phase tracking GPS receivers, a ring-laser gyro inertial navigation system, scanning and profiling laser altimeters, and (since 1993) a low-frequency ice-penetrating radar to measure ice thickness, has flown over numerous transects of the Greenland ice sheet. In excess of 100,000 kilometers of trackline have been mapped, covering all major drainage basins and characteristic geophysical regions in Greenland, as well as areas in Svalbard, Iceland, and the Canadian Arctic. The airplane location is measured precisely using differential GPS surveying techniques, allowing all altimetry data to be converted into measurements of ice surface elevation relative to the Earth ellipsoid. Analyses of these data indicate that ice surface elevations can be reliably measured with an accuracy of approximately 10 cm over baselines of more than seven hundred kilometers.

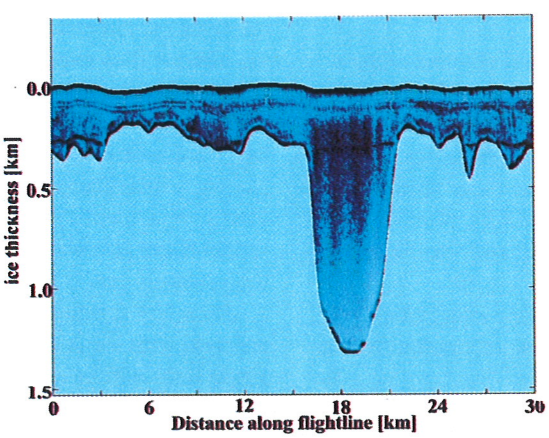
Mapping of the ice sheet by the airborne topographic mapper (ATM) scanning laser onboard NASA's P-3 aircraft typically produces a set of surface elevations along a 150-m-wide swath. With an aircraft speed of 150 m/s and a laser pulse rate of 3000 per second, this results in an average of one surface elevation per 7.5 square meters, with each elevation measurement having some uncertainty due to measurement noise, aircraft pitch and roll errors, and GPS positioning uncertainty of the aircraft. To monitor elevation change, the aircraft flies over the same ground track one or more years later, and the surface elevations are then compared. This repeatability is made possible by GPS-based navigation software developed at NASA, which guides the plane over the previous year's trajectory. Typically the centerline of the repeat flight is within 30–50 m of the centerline of the previous year's flight.

All major drainage basins on the ice sheet were mapped with the ATM in 1993 and 1994, and the flight lines will be resurveyed in 1998 and 1999 to reveal any changes in surface elevation that have occurred during the five-year interim. Subsequently it will be possible to estimate the change in the ice sheet's volume.

Data from the ATM have also been used to estimate surface velocity by tracking elevation features at the ice surface. During the 1997 field season, repeat flight lines were surveyed over four sections in the Jakobshavn drainage basin at intervals of two to six days. Using cross-correlation analysis techniques, the movement of the elevation features, the most distinct of which are crevasses, is tracked, and velocities and strain rates can be calculated. In the case of the Jakobshavn Isbrae, velocities were estimated more than 100 km upstream of the calving front. Results show that the surface velocities near the calving front are on the order of 7 km per year. This method of estimating ice velocity complements satellite-based techniques in that it offers a flexible platform that can be adapted for site-specific observations, and it simultaneously provides elevation information that is necessary for understanding the dynamics. When combined with coincident thickness data from the ice-penetrating radar, these velocities can be used to estimate discharge fluxes. The method also offers an independent means of validating ice velocities derived from SAR and visible imagery.

Coherent radar depth sounding of the Greenland ice sheet

Since 1993 a coherent radar depth sounder developed at the University of Kansas has also been flown on the NASA P-3 aircraft, making coincident measurements of the ice thickness. The radar operates at 150 MHz and is capable of measuring the polar ice sheet thickness to about 4000 m in cold ice and to a lesser thickness in temperate glaciers. As a result, coincident with the laser altimetry elevation observations, measurements have been made of the ice sheet thickness over most of the flight lines. These measurements are essential to the mass balance assessment because they provide a cross-sectional area, which, when combined with velocity estimates, allows for the calculation of ice fluxes at outlet glaciers as well as the ice sheet interior.

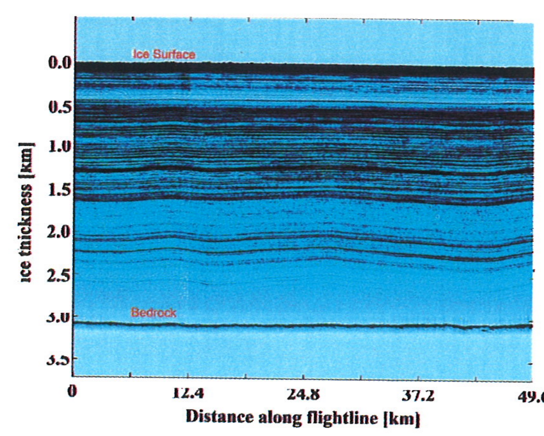


Radar echogram of the Academy Glacier's main channel. The figure covers the line from 81.44°N, 34.32°W to a position 30 km away (81.56°N, 35.94°W).

Of particular importance are thickness measurements that were made along the GPS traverse route along roughly the 2000-m contour line. These values are used to estimate the large-scale balance of the ice sheet. In addition, an extensive data set was obtained for the Jakobshavn outlet glacier, which is considered to have the highest iceberg production of all Greenland glaciers and is a major drainage outlet for a large portion of the western side of the ice sheet. In northeast Greenland, thickness measurements and echoes from the ice–bedrock interface are also being analyzed; these observations are providing insight to the characteristics of an ice stream that drains much of the northeastern portion of the ice sheet.

In addition to the clear echoes from the underlying bedrock, echoes are received from layers within the ice to depths of as much as 2.5 km. These layers can be traced throughout the ice sheet to deep-drilling ice core sites near the ice sheet summit, thus enabling the dating of the layers, providing constraints for flow models, and allowing a glimpse into the ice sheet's history. Because of the radar's ability to detect layering structures as well as thickness, it played a significant role in the selection of the North GRIP deep drilling site by providing flow-model input.

A next-generation coherent radar depth sounder (NG-CORDS) was also developed and field tested in 1997. The NG-CORDS uses microwave monolithic integrated circuits (instead of connectorized components) and a state-of-the-art digital processing system. The system has a 12-bit A/D dynamic range of 72 dB, compared to its predecessor's 8-bit A/D dynamic range of 48 dB, and it increases radar sensitivity by 3 dB. Another major advancement of the new system is that it allows low coherent integrations and permits the extraction of weaker signals. As a result the resolution is improved, and the effects of aircraft motion can be eliminated. Approximately 50% of the 1997 data were collected with the NG-CORDS instrument.



Radar echogram of the NGRIP deep drilling site covering the great circle arc from 74.88°N, 41.90°W to 75.30°N, 42.48°W.

Greenland network of automatic weather stations

The Greenland Climate Network (GC-Net), which was supported in part by a grant from the National Science Foundation, was initiated in 1995, with the goal of monitoring climatological and glaciological parameters at various locations on the ice sheet. Parameters monitored at each station include firn temperatures at 1-m intervals to a depth of 10 m; wind speed, air temperature and humidity at two levels for turbulent flux calculations; incoming and reflected short-wave radiation; net radiation; pressure; and snow height (referenced to the station mounting tower). Observations are sampled at 10-second intervals and averaged over 10-minute intervals for most of the parameters and one-hour intervals for those that are less transient (such as pressure and snow temperature). Stations have been added each year, so that the present network includes 14 stations (one in each of the major climate zones) and monitors 350 parameters. In all cases the data are stored in storage modules and are retrieved periodically. For 12 of the 14 stations the data are transmitted hourly via satellite to Boulder, Colorado, providing near-real-time climate and mass balance data for much of the ice sheet.

As of the beginning of 1998 the GC-NET database contained more than 14 station-years of measurements that have been quality-controlled and calibrated. Samples of the data can be found via the PARCA web site at http:/www.cires.colorado.edu/parca.html. The network is the first of its kind in Greenland and has been very useful in providing information on the energy and mass exchanges at the ice sheet surface, as well as providing ground-truth data for satellite observations. Analyses of the data show some very interesting and climatologically significant results.

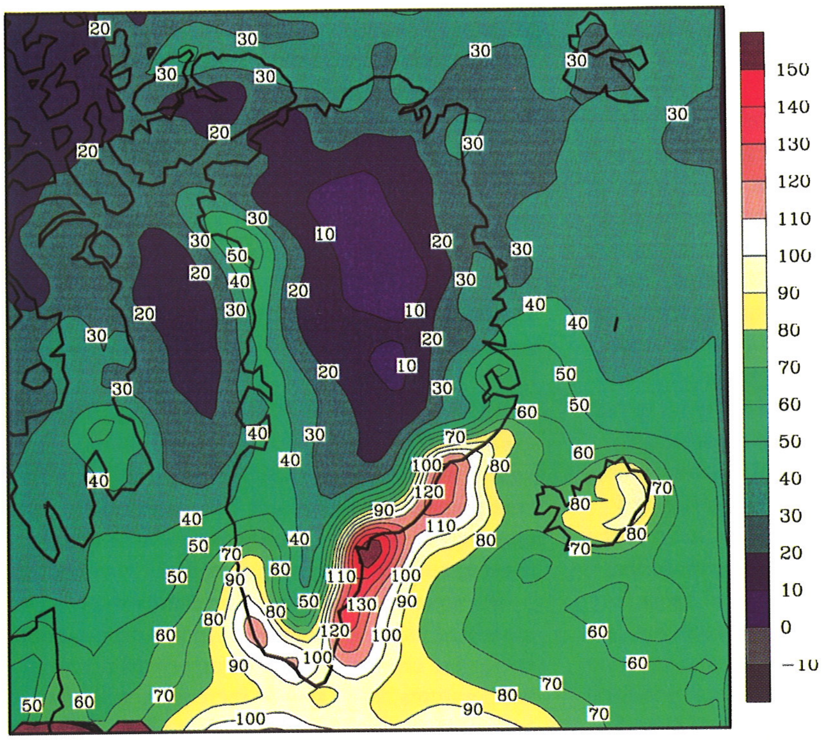
Within the Jakobshavn drainage basin, four automatic weather stations (AWSs) were installed along a profile from near the ice margin in the west to the summit of the ice sheet. These span from well into the ablation zone to the equilibrium line and onto the percolation zone. Also, slightly offset from the linear arrangement is Summit in the dry snow/accumulation zone. Data from these sites are useful for understanding variability with elevation. A mean monthly lapse rate was derived along the profile from Jakobshavn to Summit of 0.6–0.7°C per 100 m for spring and summer and 0.8–1.0°C per 100 m for fall and winter. The katabatic winds along the same profile showed an increase in directional constancy towards the coast, suggesting that they develop in a stable fashion.

A significant cross correlation was found between wind speed and surface temperature at the stations, with a correlation coefficient of better than 0.5. The data consistently show that wind speed increases precede major temperature increases by approximately 6–10 hours at each of the stations. The relationship suggests that the katabatic winds cause a turbulent mixing of the inversion in the boundary layer, bringing the higher, warmer air down near the surface. The downward movement adiabatically warms the air even further. This relation, observed mainly during winter, warms the surface of the firn and significantly impacts its structure. This in turn has important implications for microwave satellite remote sensing and for interpreting shallow ice cores.

Multiple snow precipitation events were identified using AWS data. Typical accumulation events are characterized by warmer-than-normal temperatures, wind speeds increasing with the approach of a storm and then diminishing as soon as snowfall begins, an increase in downwelling long-wave radiation flux, an increase in boundary layer stability as reflected by positive Richardson numbers, an increase in surface albedo, and a decrease in pressure. Humidity approached saturation during snow events yet was preceded by a short dry phase just before snowfall began, indicating the invasion of a different air mass. For the Humboldt AWS, wind direction during snow events is westerly, indicating that Baffin Bay is an important moisture source region. At TUNU-N (78.0°N, 34.0°W), snow events are associated with winds from the north and east.

In a spatial sense the data indicate that there are tremendous variations in all of the observed climate variables, particularly humidity and precipitation, between Humboldt and GITS (77.1°N, 61.0°W), which are only 180 km apart. Despite their proximity and similar elevation, their annual accumulation rates are 0.4 and 1.3 m of snow, respectively, in the period of occupation, which suggests that the ridge that separates the two limits the extent to which cyclonic activity penetrates the northwest section of the ice sheet. These observations are consistent with ice-core-derived accumulation rates, but the weather stations allow for a much improved interpretation of these differences.

Finally the measured mean monthly net radiation for the dry snow regions shows negative values throughout the year, with a bimodal minimum of about 30 W/m^2 in spring and fall. This indicates



Average precipitation over Greenland for 1985 to 1995 in centimeters of water equivalent on a 50- × 50-km grid. The estimates were made using an enhanced dynamic method that incorporates ECMWF analyses.

that the atmosphere is a main energy source for those regions through heat advection from warmer areas.

Data from these stations have also been used in developing models and algorithms for estimating albedo and surface temperatures of the ice sheet using advanced very high resolution radiometer (AVHRR) data. Knowledge of these parameters enables the large-scale assessment of monitoring of ice sheet energy balance characteristics. These data are also important for developing microwave emission models and interpreting microwave satellite data.

Precipitation estimates from atmospheric analyses

Observations of precipitation over Greenland are limited, they refer to different time periods, and they are of uncertain accuracy. However, the analyzed wind, geopotential height, and moisture fields in the area surrounding and including the Greenland ice sheet are available for recent years, and through the effective use of these data, precipitation on the ice sheet can be estimated. A dynamic method has been developed for retrieving precipitation data over Greenland from these twice-daily analyzed fields, and currently precipitation and accumulation over Greenland from 1957 to 1995, along with its seasonal and interannual variations, is being studied by this approach. Also under investigation with this model are the mechanisms by which atmospheric general circulation and weather systems control precipitation and accumulation over Greenland.

Precipitation estimates are made using the ω-equation method (where ω refers to vertical velocity), based on an equivalent isobaric geopotential height. Using operational ECMWF data as model input, the mean annual precipitation distribution has already been determined for the 11-year period from 1985 through 1995 on a 50-km grid. The mean precipitation shows maximum values of more than 100 cm/yr along the southeastern coast and the southwestern edge of Greenland, with a secondary band of relatively high precipitation along the western coast. A large area of very low precipitation (less than 20 cm/yr) dominates the northern interior region.

The retrieved precipitation amounts for 1985–1995 are being compared with published accumulation maps, as well as the accumulation rates from recent ice cores. Preliminary analysis shows an average difference of 10% for these comparisons. The amplitudes of the interannual variations of the mean precipitation over all of Greenland are not large during this 11-year period. The largest value is 472 mm/yr in 1987, and the smallest is 309 mm/yr in 1995. The mean for the entire ice sheet is 376 mm/yr. This compares very favorably to the Ohmura and Reeh's estimate of 340 mm/yr.

Model results also show a significant negative correlation between the monthly precipitation and variations in pressure patterns in the northern Atlantic Ocean, known as the North Atlantic Oscillation (NAO), particularly in winter. For the entire ice sheet, there is a –0.75 correlation, and for the southern portion, where most of the precipitation falls, the correlation coefficient is –0.80. Thus, the position and the intensity of the Icelandic low significantly impact the amount of precipitation on the ice sheet. The "Greenland below" condition (lower temperatures associated with a strong NAO) is associated with lower precipitation levels, and the "Greenland above" condition (higher temperatures associated with a weaker NAO) is associated with higher precipitation. The results indicate that the atmospheric circulation over the North Atlantic region is the primary control over accumulation in Greenland.

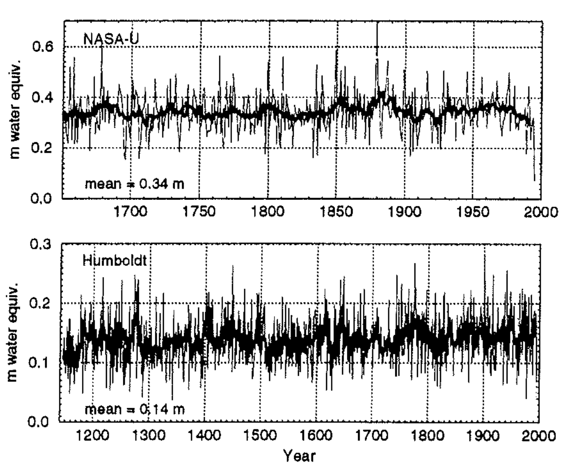
Accumulation estimates from ice cores

Year-by-year accumulation estimates are being developed for the 26 individual cores from 13 locations that have been collected since 1995 under PARCA. Year-by-year accumulation estimates have also been developed for the cores collected near the ice divide in north Greenland as part of the German program. Similar estimates could be developed for many of the older cores as well, though in most cases only average values have been reported. Cores developed under PARCA use multi-species chemical analyses of 20- to 150-m-deep ice cores to develop accurate estimates of annual accumulation at various sites. The ice core data are also analyzed for the interannual variability of snow accumulation rates, which is a major cause of short-period variability of ice sheet elevation and must be understood before we can infer long-term trends in ice sheet volume from observed surface elevation changes.

During the summer of 1995, 150-m firn and ice cores were drilled to determine annual accumulation rates at two Greenland sites: NASA-U (73.8°N, 49.5°W) and Humboldt Glacier (78.5°N, 56.8°W). Annual layers were identified in the cores using multiple parameters: $\delta^{18}O$ and concentrations of dust H_2O_2, NH_4^+, Ca_2^+, and NO_3^-. Using all parameters together to define annual layers resulted in a 350-year record for the NASA-U core with no dating uncertainty. For the lower-accumulation Humboldt core the dating uncertainty is about 5 years over the 852-year period of record, with no uncertainty over the past 200 years. Annual accumulation over the periods of record at the two sites averaged about 0.34 and 0.14 m water equivalent, respectively. There was no statistically significant trend in the NASA-U annual accumulation rates over the period of record. However, the Humboldt data do show an increasing trend of about 1.3 ± 0.4% per century. A set of 20-m firn cores drilled near the main 150-m cores showed that interannual variability of accumulation exceeded spatial variability at NASA-U. The spatial and temporal coefficients of variation for three cores were 0.12 and 0.24, respectively, for NASA-U. The Humboldt cores showed equal spatial and interannual variability, with coefficients of variation of about 0.27.

In 1996, 120-m cores were collected at GITS (77.1°N, 61.0°W) and at TUNU (78.1°N, 34.0°W), with several 20-m cores also collected at TUNU. In 1997, shallow firn cores were collected at eight sites around the perimeter of the Greenland ice sheet approximately between the 2000- and 2500-m elevation contours. The 4-inch cores were collected by two- and sometimes three-person teams using the "sidewinder" coring device, a mechanically associated hand auger developed at the University of Nebraska. At those shallow coring sites that were co-located with automatic weather stations, more than one core was collected in order to investigate issues of short-scale spatial variability in snow accumulation. Annual accumulation at two sites in northwest Greenland (75–76°N) had average values of 0.30–0.36 m water equivalent, and two sites in west central Greenland (71–72°N) had values of 0.40–0.42 m water equivalent. All four sites had values that were only 70–80% of that estimated from prior data and call into question the accumulation "ridge" in western Greenland that is apparent in older data.

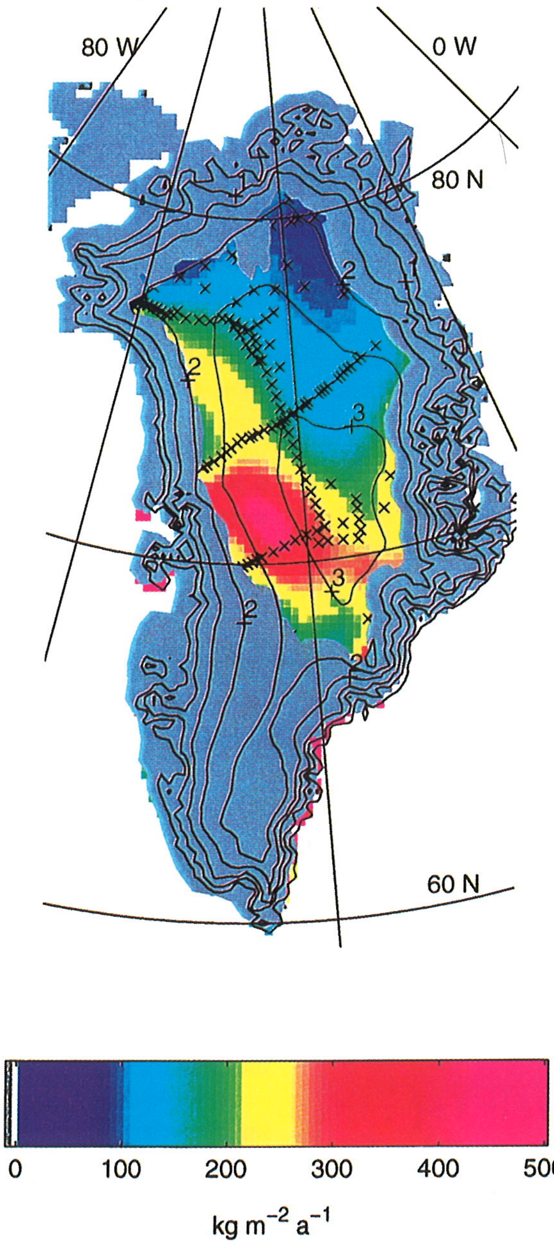
Annual accumulation for the NASA-U and Humboldt cores.



Accumulation rates from microwave remote sensing data

Because of the volume scattering characteristics of microwave radiation in polar firn, data from both active and passive microwave sensors hold information about the grain size and layering characteristics at and below the surface of the snowpack. Since both of these parameters are related to accumulation rates, microwave data can be very useful in studying accumulation on the ice sheet.

At wavelengths of a few centimeters, the layering characteristics of the firn dominate the scattering of electromagnetic energy in the firn, and particle size is not as important. Using this relationship and observations of emission behavior at a wavelength of 4.5 cm, Winebrenner and Arthern have developed a method for estimating accumulation rates in the dry snow zones of Antarctica. The technique is based on the fact that, according to field data, the mean layer thickness of random density variations with depth is linearly related to accumulation rate in the upper portion of firn. The resulting effect is a nonlinear relationship between 4.5-cm emission and accumulation rate according to the electrodynamic model of West and others. The layering structure more strongly influences the horizontally polarized emission than it does the vertically polarized emissions. Thus the polarization ratio (the normalized difference between the vertical and horizontal emission) has been theoretically related to accumulation rates in the Antarctic dry firn. This is supported by a comparison of SMMR (scanning multichannel microwave radiometer) brightness temperatures to field data at this wavelength, once buried snow crusts are accounted for.



Accumulation rates derived from SMMR at 4.5-cm wavelengths. Areas prone to melting are shown in gray. Crosses show the pit and core locations on which previous maps were based. The topography contours, labeled in kilometers, are from Ekholm.

Similarly accumulation rates in Greenland should be retrievable from the polarization ratio as well. In practice, however, the spatial resolution of the 4.5-cm SMMR observations (approximately 150 km) complicates matters by combining dissimilar firn into single pixels. Fortunately emission from dry firn in Greenland, especially in winter, shows very little temporal variation. This makes it possible to combine many partially overlapping swath observations and sharpen the spatial resolution. Accumulation estimates that have been made for Greenland based on this technique are in good agreement with the accumulation map of Ohmura and Reeh, capturing the low accumulation in the northeast portion of the ice sheet and the local high accumulation center at about 71°N, 45°W.

At shorter wavelengths, on the order of 1.5 cm, scattering particle size begins to become increasingly significant. Since snow grain size is a function of accumulation rate, a second method for estimating accumulation is based on microwave emission at 1.55 cm, which has been shown to vary hyperbolically with accumulation. The relationships have been demonstrated for the dry snow zones in Greenland and Antarctica, and microwave-based accumulation maps are being developed. The relationship at this shorter wavelength, however, is somewhat complicated by snow metamorphism and the development of hoar layers at and near the surface.

Accumulation is also being investigated at high vertical resolution by a technique that correlates the stable isotope ratio profiles (δD and $\delta^{18}O$) from snow pits with passive microwave brightness temperature trends. These analyses have allowed the amount, rate, and timing of density-corrected accumulation to be determined at locations around Greenland with subseasonal resolution. In addition, this approach is being tested across large portions of Greenland's interior for comparison to precipitation estimates from atmospheric data. This work is progressing through a collaboration with scientists involved in the Alfred Wegner Institute North Greenland Traverse. The combined snow pit data, in conjunction with analysis of the microwave signal, will provide a range of details on the subseasonal accumulation in Greenland.

Ice sheet mass balance from GPS traverses

To assess the large-scale balance of the ice sheet, a comprehensive survey of ice velocity has been measured at regular intervals, mainly along the 2000-m contour line, around the entire ice sheet. Repeated GPS data were collected at these sites with time separations between measurements of one or more years. In total, there were more than 400 individual site occupations at about 180 stations. The sites were established by planting an aluminum pole vertically in the ice, with a flagged bamboo pole planted nearby to make the site easier to find for the next occupation. The sites were usually 30 km apart, with some areas of denser spacing on the western slope of the ice sheet and a region with 40-km spacing in the northwest. Prior to 1995 the sites were visited by snowmobile traverse, but since then the work has been done using a ski-equipped Twin Otter aircraft. By comparing the locations of re-surveyed poles and accounting for the time separation between surveys, the surface velocity at each location is determined.

Ice thickness was also measured along the velocity traverse using the CORDS airborne low-frequency radar (described above). After scaling the surface velocity to account for the vertical flow gradient within the ice, and combining it with thickness measurements, we estimated the total volume of ice discharged across each segment of the traverse. The calculated ice fluxes for each segment are then compared to the total snow accumulation within the ice sheet catchment area inland from the velocity traverse that is associated with that segment. The catchment areas are estimated by reconstructing the flow lines passing through each segment between the velocity stations and assuming that the ice moves in the direction of maximum regional slope. Slopes and flow directions were determined by analyzing a smoothed version of the surface topography data set of Ekholm. By comparing the measured ice flux to the balance velocity estimates, the large-scale mass balance, or rate of thickening/thinning of the ice sheet, can be inferred. Initial results indicate that, taken as a whole, this interior portion of the ice sheet is almost in balance but with localized regions thickening or thinning by 10 cm or more per year.

This analysis is complete for most of the traverse, with a major gap in the southwestern quadrant of the ice sheet, where ice thickness has yet to be successfully measured. Deep ice in this region is warmer than elsewhere, severely reducing the radar penetration. Nevertheless, planned improvements to the CORDS depth sounder are expected to resolve this problem during the 1998 field season.

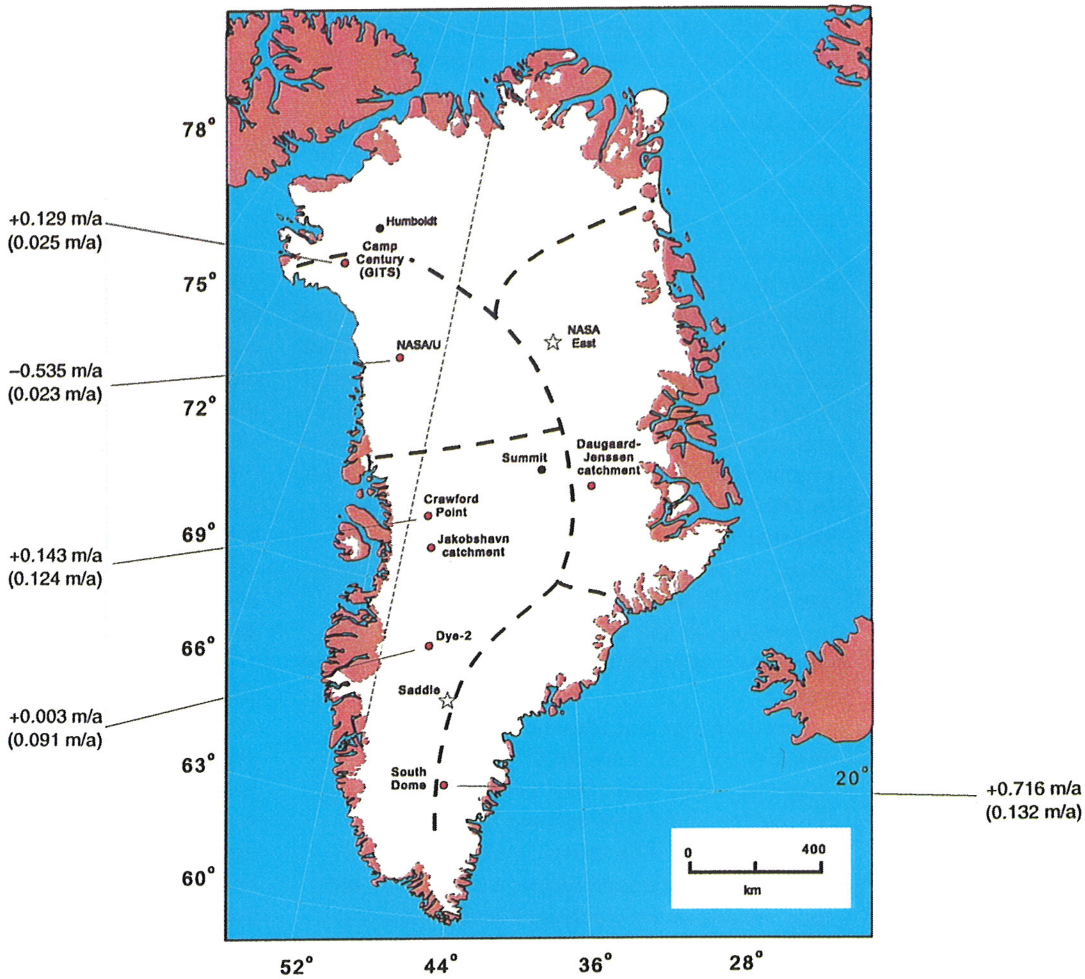
Localized ice thickness changes

In an effort to determine local rates of changes in ice thickness at various sites in Greenland, precise measurements are made of the vertical velocities at shallow drill holes. These measurements are compared with accumulation rates at the same location; if the two quantities differ, the ice sheet is assumed to be thickening (when accumulation exceeds downward velocity) or thinning (when the reverse is the case) by the difference of these two terms. The purpose of this investigation is to identify areas of large thickness changes for more detailed future studies and to interpret elevation changes detected by repeated airborne and satellite altimetry.

Vertical velocity is obtained from repeated GPS surveys of markers anchored at various depths in the firn or ice. Placing the markers at depth avoids vertical motion caused by variations in snowfall and firn compaction. In most cases, markers are placed in hot-point drilled holes at depths ranging from 5 to 25 m. If markers can be anchored in solid ice, then the correction for firn compaction does not need to be made. At the NASA-U and Humboldt sites, markers were installed in ice at the base of the approximately 150-m-deep ice core.

Each site has five or six markers plus one reference point. A marker consists of a piece of metal stock frozen to the base of a hole. Aircraft wire of a length sufficient to reach the snow surface is attached to the piece of metal. A crimp fixed to the wire at the surface serves as the reference point for the surveys, and the relative elevation of the crimp is measured while a constant amount of tension is applied to the wire. Measurements of the crimp location repeated over intervals of one or more years provide the vertical velocity of the marker.

Quick local surveys using stop-and-go kinematic GPS and optical leveling connect the various markers and the reference point to one another, and precise relative elevations are computed using relative phase tracking. The two survey methods are used to ensure consistency. A suite of markers at different depths (and densities) is used to test if the firn compaction follows Sorge's Law,



Observed localized thickening (positive) and thinning (negative) rates. The standard deviations of the measurements are given in parentheses. Sites marked with a star indicate new sites occupied in the 1997 field season, while those marked with filled circles have been occupied previously. Only those sites for which values are shown have been revisited. The remaining sites will be revisited in the 1998 field season.

which states that firn density at any depth does not change over time, and as a check on proper marker placement.

To convert vertical velocity to thickening or thinning rates, compaction, local topography, and accumulation rates must be known. Compaction is assumed to follow Sorge's Law, and local topography is measured with the ATM and local kinematic GPS surveys. Accumulation rates are determined from the firn core. While large-scale accumulation rates are still not well known, the data from the ice cores provide very accurate estimates at the core location for recent years.

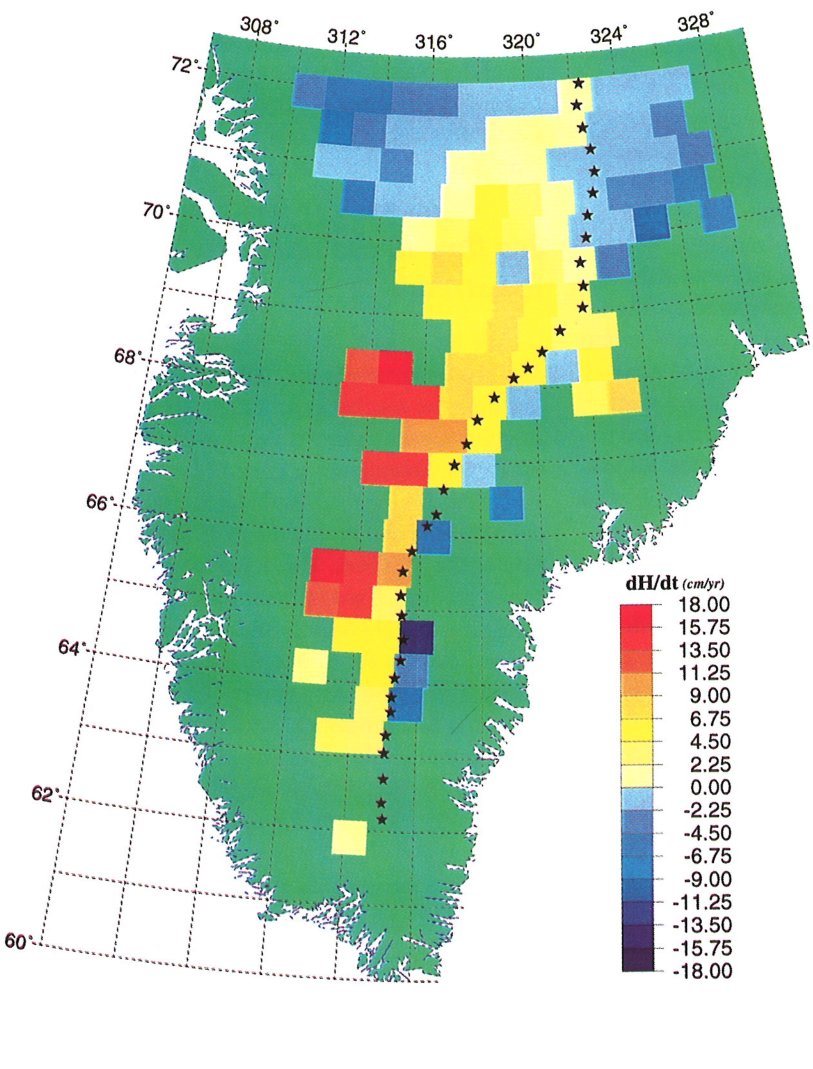
Twelve sites have been installed on the Greenland ice sheet, and as of 1997, five sites have been re-visited and studied in detail. Results indicate a slight thickening at most locations on the western flank, with one area of severe thinning near NASA-U. The southernmost site shows a pronounced thickening in excess of 70 cm/yr. These thinning/thickening rates are consistent with the ice sheet mass balance observations from the GPS measurements as described in the previous section.

Greenland ice surface elevation changes from satellite radar altimetry

Estimates of the overall mass balance and seasonal and interannual variations in the surface mass balance are obtainable from time series of ice surface elevations measured by satellite altimetry. Although satellite radar altimetry has significant limitations in coverage and accuracy over sloping surfaces, information on ice-sheet surface elevation changes has been derived in the past for central parts of the Greenland ice sheet south of 72°N. In the nine years since the original study, which suggested a thickening rate of 23 cm/yr, significant improvements in the analysis of radar altimetry data have enabled more accurate and detailed estimates of elevation changes over longer time periods. This is largely attributable to improved knowledge of orbital parameters as well as the development of better retracking algorithms. Consequently recent investigations have led to improved estimates in changes in the ice sheet elevation.

Davis and others have re-examined elevation change estimates for the Greenland ice sheet by incorporating a global method for analyzing the altimeter orbit error present in the ice sheet data sets. Because the predominant radial orbit error is a long-wavelength signal concentrated at the circular frequency of the orbital period, they used a global analysis of ocean altimeter data sets to help correct for orbit errors. For the Geosat–Exact Repeat Mission (ERM: 1987–1988) and the Seasat (1978) mission, crossover data sets were created with respect to a reference (mean) ocean surface. The radial orbit error was identified by passing the sea height crossover residuals through a stochastic filter designed to estimate the time-varying amplitudes of the sinusoidal orbit error function and the measurement system bias that may be present in inter-satellite comparisons.

Changes in elevation derived from Geosat/Seasat radar altimetry comparisons. The stars represent the ridge of the ice sheet. (From Davis et al. 1998, reprinted with permission from the American Association for the Advancement of Science.)



The resulting orbit error corrections were applied to the Seasat and Geosat–ERM Greenland data sets, and an elevation change analysis was performed by computing the average change in elevation divided by the average time interval using all crossovers. A spatial analysis reveals large geographic variations in elevation change from –15 to +18 cm/yr. After isostatic adjustment a spatial average of 32,283 ERM/Seasat crossovers yields a 1.7 ± 0.5-cm/yr growth rate from 1978 to 1988. This growth rate is less than 10% of that from earlier analyses, due primarily to a progressive improvement in the knowledge of the satellite orbits. Given the large spatial variations in elevation change, this averaged growth rate is too small to determine whether or not the Greenland ice sheet is undergoing a long-term change due to a warmer polar climate.

Elevation changes obtained between Seasat (1978) and Geosat (1985–1989) are affected by the short, three-month period of Seasat and interannual variations in the seasonal cycle. To address these issues a separate analysis using only Geosat data (1985–1989) was performed. The four years of Geosat data showed a thickening of about 7 cm/yr south of 72°N. Seasonal variations in elevation, caused by variations in accumulation, firn compaction, and melting, were also observed in the data. These range from a 14-cm peak-to-peak amplitude cycle with a minimum in July at 2200- to 3300-m elevations, to about 2 m with a minimum in late September in the upper ablation zone.

Zwally and others did a similar re-analysis of Seasat and Geosat data but to down to about 700 m in elevation, covering a significantly larger part of the ice sheet. The results are qualitatively similar but differ in magnitude. The differences are largely attributable to the changes in the area below 2000 m, which were not included in the earlier work. Zwally's results show an average thickening of the ice sheet south of 72°N on the order of 5 cm/yr but with larger uncertainties at the lower elevations.

Preliminary analysis of ERS-1 radar altimetry data (1992–1996) above 76°N suggests a thinning of 11 cm/yr above 2700-m elevations on the northeast part of the ice sheet and a thickening at lower elevations with a 10-cm/yr maximum at 1200- to 1700-m elevations. On the northwest part of the ice sheet, the data suggest a thinning of 20 cm/yr above 2200 m and a thickening at lower elevations with a 24-cm/yr maximum at 1200- to 1700-m elevations. These results from ERS-1 data are very preliminary and are not confirmed by other PARCA investigations.

The analysis of radar altimetry data to measure changes in elevation has a number of limitations, and beginning in 2001, NASA's Geoscience Laser Altimeter System (GLAS) will significantly improve the range accuracy, the orbit accuracy, and the spatial coverage for measuring seasonal and long-term changes in ice sheet elevation.

Ice velocity and discharge flux from interferometric synthetic aperture radar

In recent years, tremendous progress has been made in the use of synthetic aperture radar interferometry (InSAR) to study the surface ice velocities on the Greenland ice sheet. Using near-repeat passes of ERS-1 and -2 satellites, relative phase differences of the returns provide information on the topography and relative velocities between different points in the image when combined with elevation data from satellite and airborne altimetry. When these velocities are compared to fixed points near the coast or velocities measured in situ on the ice with GPS receivers, they can be converted to components of absolute surface velocities. In addition, InSAR has recently been used to observe flexure in floating glacier tongues, allowing for the detection of the hinge lines, which are a proxy for the grounding lines.

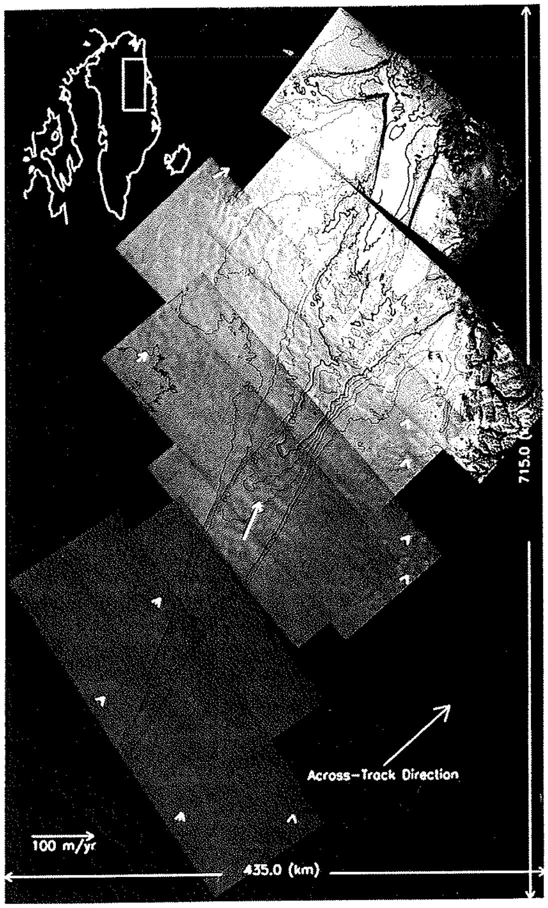
One significant application of this technology is in studying ice discharge in the major drainage glaciers. By combining surface velocities with ice thicknesses, ice fluxes are calculated. Ice thicknesses are determined by assuming hydrostatic equilibrium near the grounding line and also from the CORDS observations. When these fluxes are compared with flux estimates at the calving fronts, the grounding line flux is found to be much greater than that at the calving front. For 14 glaciers in north and northeast Greenland, they differ by a factor of 3.5 on average, and as much as 20 for Petermann Glacier. These differences are attributed to basal melting, which previously was assumed to be minor. These basal melt rates, which are inferred assuming steady-state conditions, are ten times greater than those recorded on Antarctic ice shelves; the implication for mass balance estimates, as well as freshwater influx to the surrounding seas, is large.

Accumulation data from Ohmura and Reeh and ablation estimates from Reeh's positive degree-day model were used to calculate the ice fluxes necessary for balance in the drainage basins that feed these outlet glaciers. A comparison of these values to estimates at the grounding line suggests a mass loss of 8 ± 7 km^3/yr in northern Greenland. Further mass balance analysis, recently complemented with new glacier additions, continues to indicate that the northern sector of the ice sheet may be slowly thinning. It has also been found that the grounding line of Petermann Glacier retreated by several hundred meters between 1992 and 1996, which is consistent with the suggested thinning trend of north Greenland glaciers.

A similar approach, which will combine ERS interferometry data from 1995–1996 and the CORDS system measurements collected in 1998, is being used to characterize the ice discharge of the entire coast of East Greenland. When the major outlet glaciers in the west are examined in the future, a complete assessment of the entire ice sheet mass balance will be possible.

Ice flow in the northeast Greenland ice stream

The ice sheet thinning suggested by InSAR analysis underscores the importance of understanding the mechanisms and behavior of the major drainage areas throughout Greenland. The northeast Greenland ice stream, first identified with SAR imagery, extends far inland to near the central ridge and drains much of the northeast portion of the ice sheet. This ice stream feeds three outlet glaciers. Two of these glaciers, Nioghalvfjerdsbrae (79°N Glacier) and Zachariae Isstrom, are responsible for 57% of the 49.2 km^3/yr discharged from the north and northeast. The third glacier is Storstrommen, which is more southerly. Consequently understanding its behavior and the mechanisms that drive it are of considerable interest. It is not clear why the ice stream extends so far inland and contributes so much to the removal of ice from the interior. Also, it is not clear whether the ice stream flows along a well-developed channel. Until recently the available data on the bedrock topography were not of sufficient resolution to detect the presence or absence of a channel.



Interferometrically derived estimates of the across-track component of velocity (black contours for the northeast Greenland ice stream). The white arrows show the velocity vectors measured using GPS. InSAR estimates agree with the GPS measurements to approximately 3 m/yr.

SAR interferometry controlled by GPS field surveys is providing a detailed picture of the flow of this ice stream. The flow patterns in the onset area are more complicated than had previously been reported, with an apparent second tributary entering from the south. Downstream, the flow changes character and seems to deviate from what would be expected from simple balance flux estimates. While this deviation may be due to problems with the accumulation and ablation data used for estimating the balance, it may also reflect a variability in the system related to the surging behavior of Storstrommen Glacier.

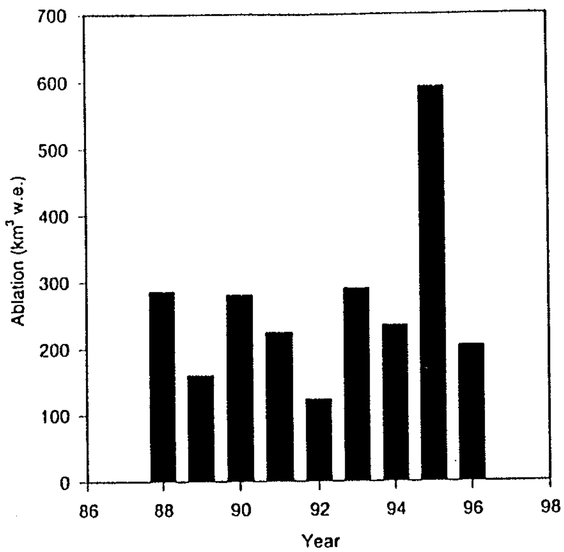
In addition to the ice flow information, newly acquired radio-echo sounding profiles and altimetry data are helping to define the character of this large feature. Recent surveys with the University of Kansas CORDS system across and along the ice stream are providing information on the bedrock topography and the ice–bedrock interface. Multiple-azimuth photoclinometry using AVHRR data is also improving our understanding of the surface topography that is produced by the rapid ice motion. Initial results from this work show that the margins of the stream are topographic troughs and that the undulation field on the stream is strong enough to produce closed basins in several areas.

Ablation rate estimates from passive microwave observations

Passive microwave satellite sensors (SMMR and SSM/I) have been used to map the spatial extent and frequency of snowpack melting on the ice sheet, with a continuous time series available since October 1978. The derivation of melt frequencies from microwave data is based on the increase in microwave emissivity as liquid water is introduced into a previously dry snowpack. A simple radiative transfer model is used to estimate the SMMR and SSM/I 37-GHz, horizontal polarization brightness temperatures associated with melting snow and ice. The modeled brightness temperatures are then used as thresholds. If the observed brightness temperature exceeds the modeled brightness temperatures, melt is said to have occurred that day.

The duration of the ablation season is estimated by examining the melt characteristics of the ice sheet derived from the gridded set of SSM/I data. From these estimates, surface temperatures are also calculated by assuming that the microwave melt frequency (that is, the percentage of days with melt) calculated on a monthly basis is equal to the probability that the surface temperature exceeds 0°C. The mean monthly temperature and the number of positive degree-days (PDDs) can then be determined. A snow and ice melt model is used to account for different degree-day factors for snow and ice surfaces and to account for the formation of superimposed ice. Potential ablation rates are calculated by multiplying the number of PDDs by the appropriate degree-day factor. Actual ablation does not occur until the amount of superimposed ice reaches 60% of the annual accumulation rate. The model uses degree-day factors of 0.008 m/d°C for ice and 0.003 m/d°C for snow and a standard deviation of daily temperatures of 5°C. Since these are the same values used in the European Ice Sheet Modeling Initiative (EISMINT), they should be sufficient.

Mass balance calculations give an overall average annual accumulation of approximately 530 km^3/yr (from the EISMINT estimates) and a mean annual ablation rate of 230 km^3/yr (from the method described above). The ablation rate shows a large range during 1988–1996, from 100 to 500 km^3/yr, but most years experienced 200–



Annual total ablation rate for Greenland estimated from SSM/I.

300 km^3/yr. Approximately 13% of the ice sheet experiences net ablation, but this varies from 8% (1992) to 23% (1995).

Facies changes from scatterometer data

Although originally designed to measure ocean winds, spaceborne microwave radar scatterometers such as the NASA scatterometer (NSCAT) can be used effectively to study changes in large polar ice sheets. New imaging techniques facilitate the use of historic and contemporary scatterometer data to investigate decadal climate change and its influence on the radar characteristics of ice sheets such as that on Greenland. Data from the Ku-band NSCAT, as well as data from the C-band European Space Agency's ERS-1/2 AMI (EScat) and the NASA Seasat scatterometer (SASS), are being used to study the backscattering characteristics of the Greenland ice sheet since 1978. Key snow and ice facies are clearly delineated on the basis of the radar backscatter cross section and its variation with time. Differences between images acquired at intervals also enable short-term seasonal or longer-term interannual changes to be detected.

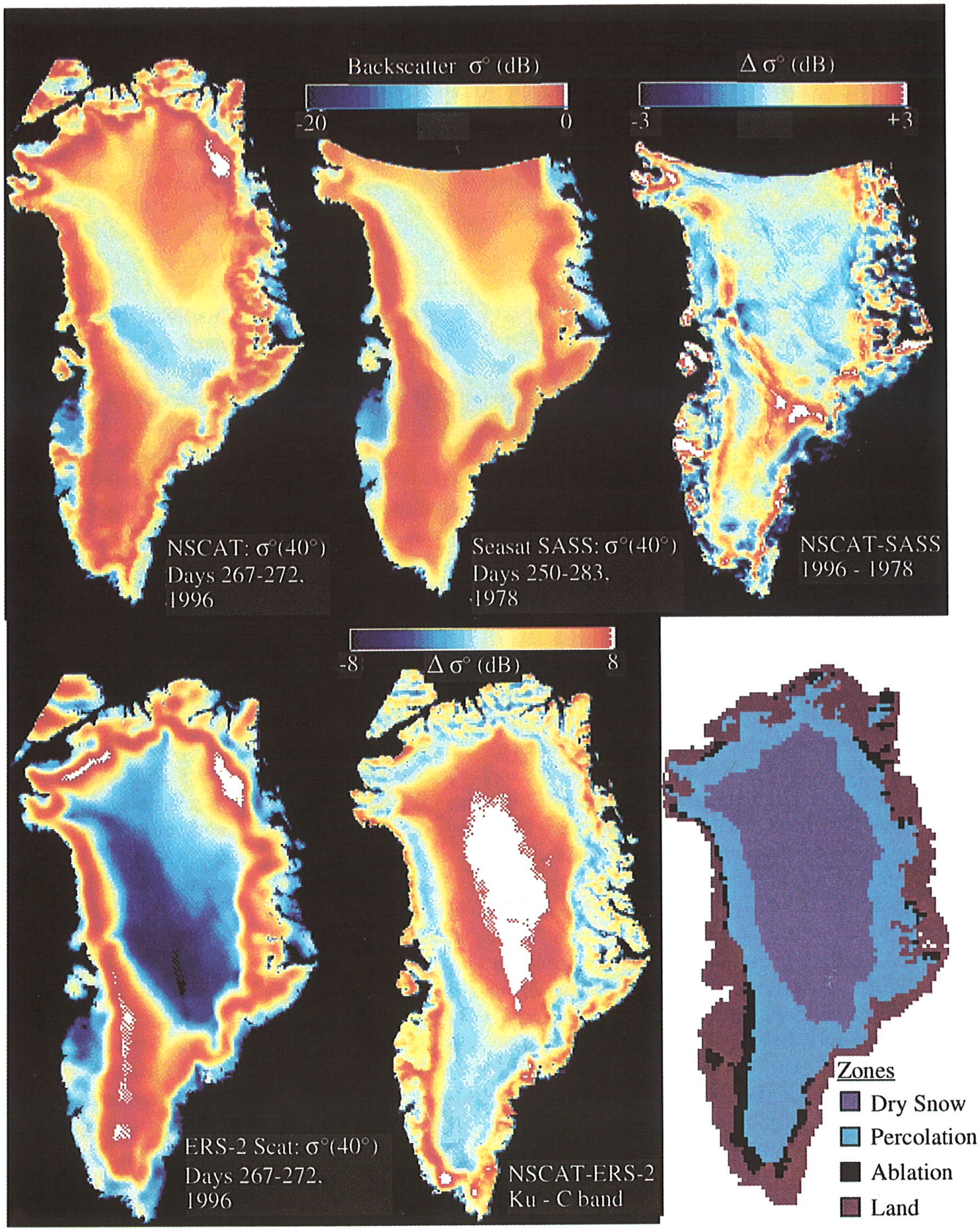
Comparisons between Ku-band seasonal backscatter characteristics in SASS (1978) and NSCAT (1996) data enable detection of 18-year changes in the location and extent of the dry snow zone. This zone is the high-altitude portion of the Greenland ice sheet that normally experiences no summer melting. The results show a clear reduction in its extent since 1978, with the largest changes occurring in the southwestern part of the ice sheet. These changes are consistent with a decadal warming trend and an increase of more than 1.0°C since 1979, except for 1992 when aerosols from the Mt. Pinatubo eruptions are believed to have reduced the ice sheet melt extent. Analysis of the facies for each year from 1992 to 1996 indicates that the summer melt area has climbed upslope and encroached significantly on the dry snow zone to create the large changes observed in the difference between NSCAT and SASS backscatter. In particular, 1995 was the year of maximum melt extent within the last decade, which is consistent with the ablation estimates discussed in the previous section.

Other preliminary results suggest that NSCAT data may be useful for extracting dry-snow-zone accumulation rates, which are useful for estimating the overall balance (that is, net shrinking or growing) of the Greenland ice sheet. Research in this area is in its early stages.

Absolute gravity and GPS measurements in Greenland

One final component of the PARCA mass balance investigations examines the motions of the Earth's crust to detect variations in loading conditions caused by changes in the ice sheet mass. Ongoing changes in the distribution and volume of ice in Greenland could cause vertical crustal motion of up to several millimeters or more per year around the edges of the ice sheet. By measuring this motion, it should be possible to learn about those changes in ice. However, the viscoelastic response of the Earth to past changes in ice loading could cause vertical motion rates that are on the same order. These viscoelastic effects must somehow be removed before crustal motion observations can be used to help constrain the mass balance of the ice caps. Theoretical arguments suggest that this can be done by combining vertical motion measurements with simultaneous observations of time variation in gravity.

Multi-year simultaneous measurements of absolute gravity and GPS crustal motion are being made at two bedrock sites at the edge of the Greenland ice sheet—Kangerlussuaq and Kulusuk. Continuous GPS measurements have been made at Kangerlussuaq since July 1995, and three two-week occupations with an absolute gravimeter have also been carried out. GPS results indicate that the crust is subsiding at a secular rate of about 6–8 mm/yr, consistent with the GPS measurements. (For the Earth's elastic response to present-day loading, 1 mm of subsidence corresponds to



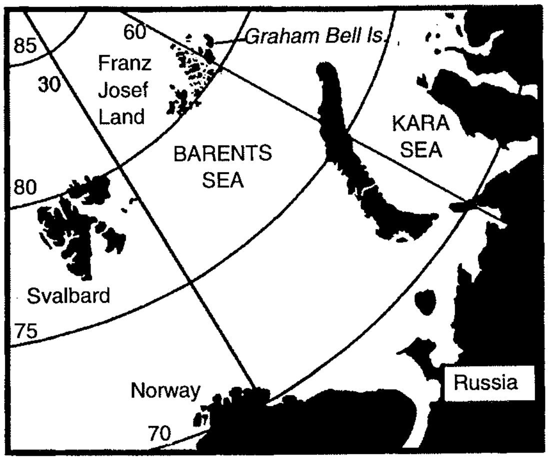
Backscatter images collected by three spacecraft scatterometer instruments. The images are (left to right) an NSCAT backscatter coefficient image for Julian days 267–272, 1996; a SASS backscatter image for days 250–283, 1978; an NSCAT–SASS backscatter difference image (i.e. 1996–1978); an ERS-2 (EScat) backscatter image for days 267–272, 1996; an NSCAT–ESCAT (Ku – C band) backscatter difference for days 267–272, 1996; and the primary snow and ice zones identified from the combined radar images. The patterns of high and low backscatter values represent zones of different snow and ice physical characteristics. The map on the lower right indicates the primary facies: land, ablation, percolation, and dry snow zones. These zones are determined by defining thresholds in the radar backscatter that allow for the facies distinction. By tracking the areas that fall within the appropriate backscatter thresholds, the changes in the facies as well as their interannual variability are determined.

about 0.3 microGals of gravity increase.) These preliminary results suggest the ice sheet may be thickening at the rate of a few tens of centimeters per year averaged over a few hundred kilometers from Kangerlussuaq. However, a longer data span is required to support this interpretation. Analysis of the scatter of the data collected with GPS and gravity over the last three years indicates that the frequency of the gravity measurements determines how long it will take before the viscoelastic deformations can be separated from the elastic deformations. Annual measurements over the next five years should allow these effects to be separated.

Franz Josef Land ice core analysis

Though not directly a part of the PARCA program, an important complement to the research done in Greenland is the analysis of ice cores from nearby Franz Josef Land on the northern rim of

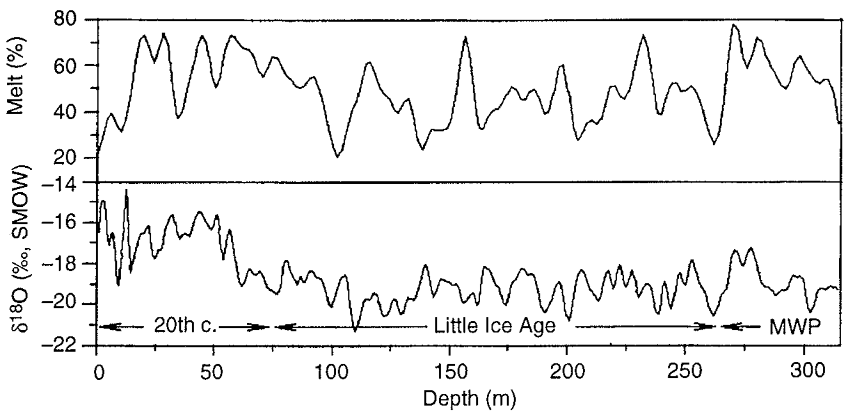
Location of Graham Bell, Franz Josef Land.



the continental shelf that underlies the Barents Sea. Through a joint effort between researchers from the Byrd Polar Research Center (BPRC) and the Russian Academy of Science, short- and long-term changes in the Arctic climate and sea ice cover are being studied. These investigations provide a large-scale view of the regional climate changes and aid in interpreting the Greenland observations.

The climate of this archipelago is influenced greatly by the intrusion of Atlantic-derived cyclonic systems that feed moisture into the region, and as a consequence the area experiences seasonal extremes, that is, mild summers and harsh winters. These factors make Franz Josef Land a strategic location for studying changes in sea ice cover in the Arctic, since it lies in the region between the modern-day seasonal maximum (February) and minimum (September) sea ice cover, as derived from passive microwave satellite data. Accordingly these satellite measurements have been used in conjunction with stratigraphic profiles of sea salt aerosols (Cl^-, Na^+, SO_4^{2-}) from short cores (up to 24 m) drilled in 1994 to demonstrate that the ice core sea salt record can be used as a proxy for changing summer sea ice cover in the surrounding Barents Sea. This sea ice record will certainly reflect regional climate variability (for example, SSTs, salinity) but may also be sensitive to large-scale ocean circulation changes.

Core results from Graham Bell, Franz Josef Land, showing the melt percent smoothed over 1-m intervals and the oxygen-18 isotope values smoothed over 1-m intervals.



In March–April 1997, two cores, 36.4 and 314.8 m long, were retrieved from Kupol Vyetreniy (Windy Dome) on Graham Bell Island. The observations of visible ice stratigraphy have been reduced to a continuous record of melt percent, and the $\delta^{18}O$ survey has recently been completed at BPRC. Both records indicate a strong change in character between depths of 60 and 100 m. The initial interpretation is that this represents the transition from the last century back into the Little Ice Age (LIA), the period of lower global temperatures that persisted from around 1450 to 1850 A.D. Less apparent is a trend towards less negative $\delta^{18}O$ values and higher melting below 250 m, which may represent the final stage of the Medieval Warm Period (MWP, 1000–1450 A.D.). Hence, the initial interpretation is that the 315-m ice core represents a continuous climate record of perhaps the last 800–1000 years.

The final, fully constrained age scale will emerge from the detailed chemistry and dust records from the longer core, now well underway. Continuous fine-resolution profiles (at 4-cm intervals) of major anion concentration (Cl^-, NO_3^-, and SO_4^{2-}), particulate concentration/size distribution, and $\delta^{18}O$ have been completed down to 102 m deep. So far, differences are obvious between the long-term (multi-decadal) trends of the three major anions. Whereas chloride concentrations attain peak levels in the zone from 35 to 55 m deep (the early- to mid-20th century), sulfate levels rise more consistently from 100 m towards the top (present) and indicate a potential anthropogenic source. Mean nitrate levels were relatively unchanged until very recently, with several large pulses occurring mainly in the last 40 years. While the increased melting and percolation in the zone from 20 to 60 m deep partially obscures the seasonal oscillations in sea salt chloride, it is evident that a strong annual signal is re-emerging as the colder LIA ice has now been reached. Therefore, a majority of the core is expected to have strong age control once this lower "floating" time scale can be fixed in absolute time, which will likely be accomplished through the identification of volcanic horizons.

With continuous team effort by members of the Ice Core Paleoclimatology Group at BPRC, detailed analysis on both Graham Bell ice cores should be completed by November 1998. As progress is made downcore, dating will continue,

Status and results of various PARCA activities

Parameter studied	*Method*	*Region*	*Time period*	*Results/status*
Elevation change	Satellite radar altimetry	ERS-1/2: south of 82°N Seasat: south of 72°N Geosat: south of 76°N	1978–present	Thinning in SE; thickening in SW; spatial variability of ± 10 cm; seasonal amplitude of ±15 cm
Elevation change	Aircraft laser altimetry	Entire ice sheet	1993/94–1998/99	Will be completed after 1999 field season
Localized thickness changes	Vertical motion of markers in shallow drill holes	Representative sections of the ice sheet	50-800 years (depending on core depth)	Thickening in south; variable in west; completion in 1998
Mass change	Absolute gravity and GPS measurements at coastal sites	Area within 500 km of Kangerlussuaq or Kulusuk	Present day mass change (5–10 years)	Kanger: 3-yr data; Kulusuk: 2-yr data. Annual collection will continue beyond 2000; Crust subsidence of 6-8 mm/yr observed
Accumulation	Ice cores	Core sites	Decades to centuries	*1995:* two 150-m cores and six associated shallow cores: results in this report; *1996:* two 120-m cores and eight shallow: results available fall 1998; *1997:* eight 20-m cores results by fall 1998; *1998:* fifteen 20-m cores planned; *1999:* two 150-m cores and associated shallow cores planned
Accumulation	Atmospheric modeling	Entire ice sheet	1957–1995	Complete: 1985–1995; Pending: 1957–1984; Decrease 1985–1995; correlation with NAO
Accumulation	Passive microwave	Dry snow zones	Decades	4.5-cm emission-based map is complete; 1.55-cm-based map will follow within the year
Ablation	Passive microwave	Melt zones	1979– present	Ablation rates, variability, and areas have been estimated
Ice flux	Surface GP measurements	Perimeter of approximate 2000-m contour line	1993–present	Analysis complete for western region; in progress for entire perimeter
Ice transport from ice sheet interior	InSAR, photoclinometry, laser altimetry, ice-penetrating radar	Northeast Greenland ice stream	1996–1998	Largest area of ice motion ever mapped; Single component of motion estimated for entire stream and some outlet glaciers; Full motion field in progress
Ice flux at discharge glaciers	InSAR	All major ice sheet drainage glaciers	North: 1997; East: 1998: West and South: after 1998	Thinning in northern Greenland and basal melting is major ablation component
Local climate parameters	AWS observations	14 stations with 2 more planned in for 1998	1995–present (varies with location)	All stations recording radiant and turbulent flux parameters, accumulation and snow temperatures, offering unprecedented detailed climate information for much of the ice sheet
Changes in facies	Seasat, ERS-1/2, NSCAT	Entire ice sheet	1978–present	Melt regions have advanced. 1995 showed maximum melt extent

and the complete climate record will be consigned to the time scale upon conclusion of the analysis. Efforts will then be focused on the interpretation phase of the project, including the development of the chemistry records as a sea ice proxy, and the extrapolation back in time to complete a sea ice history for the Barents Sea.

Summary and conclusion

The Program for Arctic Regional Climate Assessment has made major progress in improving our understanding of the mass balance of the Greenland ice sheet, the mechanisms that affect this balance, and its behavior in our changing climate. This is being achieved by the analysis of various mass balance parameters, either individually or as a whole, by a number of different means. All provide important complements to one another, and they suggest a thinning in the northern and southeastern parts of the ice sheet, a thickening in the southwest, significant seasonal variability, a correlation between accumulation and the North Atlantic Oscillation, increasing melt in recent years, and decreasing accumulation in recent years. Furthermore, through links with the research being done in Franz Josef Land, the history of the larger-scale Arctic climate is being addressed.

PARCA will culminate with the acquisition and analysis of the repeat laser altimetry measurements in 1998 and 1999. These observations, in conjunction with the other components of the program, are expected to address the questions of the change in mass of the ice sheet as well as its spatial variability. Results from the program have enhanced, and will continue to improve, our understanding of the ice sheet and its role in our changing climate at an unprecedented level. The science, techniques, and improved understanding of the ice sheet will be extended to future analyses of Antarctica. They will also enable a more comprehensive interpretation of data from the GLAS instrument following its launch in 2001.

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Polar Exchange at the Sea Surface

An EOS Interdisciplinary Investigation

This report was prepared by D. Andrew Rothrock, POLES Principal Investigator. The team of POLES investigators includes J. Francis (Rutgers University), J. Key (Boston University), S. Martin, D. Rothrock, A. Schweiger, M. Steele, D. Thomas, and J. Zhang (all of the University of Washington).

POLES and the NASA Polar Program

The Polar Exchange at the Sea Surface (POLES) program is one of a number of interdisciplinary investigations within EOS (Earth Observing System), a program of the National Aeronautics and Space Administration (NASA). The primary goal of EOS is to advance the scientific understanding of the entire Earth system.

POLES objectives

The overarching goal of POLES is to provide an accurate quantitative understanding of the exchanges of energy, momentum, and water in the atmosphere–ice–ocean system of polar regions, so that we can determine their role as an indicator and agent of past and future global climate change. In particular the objectives of our research are as follows:

- Determine the heat and moisture balance of the polar atmosphere, including the surface heat balance, radiation to space, and the transport of heat and moisture into the polar atmosphere from midlatitudes;
- Determine more accurately the amounts of polar clouds and their effect on the surface and top-of-atmosphere radiative balance;
- Determine the turbulent surface fluxes of heat, momentum, and moisture and how they and radiative fluxes interact with the atmospheric boundary layer, and determine the boundary layer stability;
- Determine a "plumbing diagram" for heat and fresh water in the Arctic Ocean, their seasonal and interannual variabilities, and their impact on water mass formation and the global thermohaline circulation; and
- Determine the processes controlling sea ice mass and momentum balance and extent, and their role in polar air–sea exchange.

These goals contribute to the broad goal of the Earth Observing System, which is "to advance the scientific understanding of the entire Earth system by developing a deeper understanding of the components of that system and the interactions among them, and how the Earth system is changing."

More information about POLES is available on their home page: http://psc.apl.washington.edu/poles/

We want to understand what the Arctic air–ice–ocean system is doing right now. To accomplish this, POLES attacks these goals along four avenues:

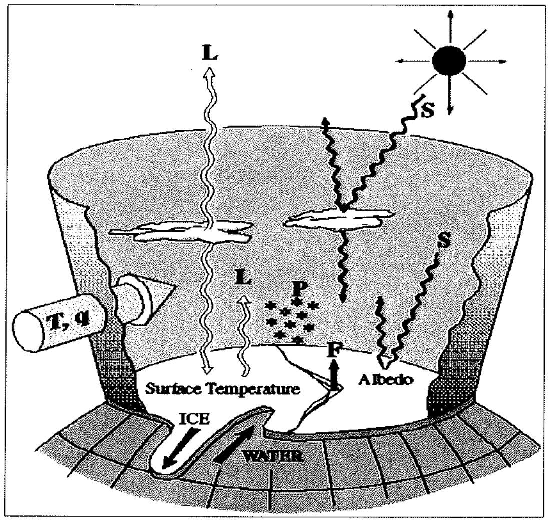
- By developing, assessing, and improving satellite algorithms in polar regions;
- By producing polar data sets of clouds and other atmospheric properties, of the sea ice state, and of ocean behavior;
- By modeling polar processes and the combined atmosphere–ice–ocean system; and
- By analyzing and quantifying polar processes and climate change signals from both data sets and model output.

We have focused on assimilating satellite and other data into our coupled models. This philosophy is distinct from most Arctic modeling studies, which have generally ignored these data or used them only cursorily for validation. Such studies are driven only by solar input or with surface forcing data and are thus free to represent coupled air–ice–ocean processes completely internally. In POLES, on the other hand, our models are constrained by as many observations as possible. We use these models to advance the study and understanding of polar processes on the time scales determined by satellite data availability—the last two decades. With the deeper understanding thus gained, we can learn how to better simulate future climates as well.

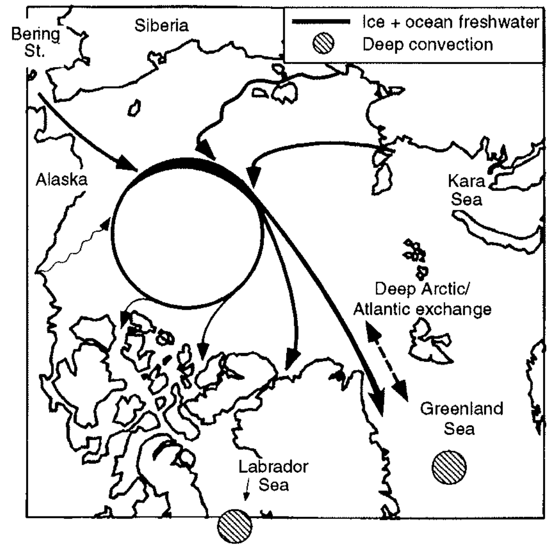
Sea ice and climate

The issues of sea ice–atmosphere–ocean interaction and its role in climate are central both to POLES and to NASA's Polar Program.

Surface heat balance and "polar amplification." The polar regions are the heat sinks of the global climate system. Atmospheric advection of sensible heat from lower latitudes supplies about 100 W/m^2, which is then radiated to space. The radiative balance is in turn crucially dependent on clouds, temperature and humidity fields, and the



Schematic of the heat balance over the Arctic Ocean, designed to illustrate the SHEBA Project. Heat and moisture are advected from lower latitudes (T,q) and combine with the short- and long-wave radiation (S, L) to maintain the ice cover and radiate excess heat to space.



Freshwater circulation of the Arctic Ocean. The inflows are low-salinity water from Bering Strait and fresh water from Siberian and North American rivers; the outflows are sea ice and seawater through Fram Strait and seawater through several passages of the Canadian Archipelago. Also shown are the sites of deep convection and the deep exchange of waters through Fram Strait.

surface albedo. In winter, radiation is lost to space and the surface cools, leading to sea ice growth. In summer, radiation is absorbed by the surface, especially in low albedo areas such as melt ponds and cracks or "leads" in the pack ice. The result is melting. Clouds play a crucial role. In winter they increase the downwelling long-wave radiation above clear-sky values by roughly 80 W/m^2, thus slowing sea ice growth. In summer they decrease the net radiation balance by about 40 W/m^2, thus slowing melt. In balance, a cloudier Arctic should be warmer and have less sea ice.

The albedo of sea ice is 5–8 times that of sea water. This becomes very important in climate change scenarios. For example, a warmer climate should deplete the sea ice area and extend its melt season, both effects reducing global albedo and causing further warming. This process is known as ice–albedo feedback. Sea ice models show large sensitivities to albedo, yet this quantity is neither well observed nor well represented in models.

Simulations in which CO_2 levels are doubled predict that the polar winter will warm up twice as much as at lower latitudes. This phenomenon, called "polar amplification," is generally ascribed to the slow release of excess heat absorbed in summer by the ocean and ice cover. It is a sign of our poor present understanding and observational knowledge of polar climate processes that, although climate models suggest observable changes, recent climate records show only the faintest signs of polar warming and of declining sea ice extent.

Role of the Arctic Ocean in global ocean thermohaline circulation. The Arctic Ocean is a great ice-covered estuary that funnels fresh water from rivers and the North Pacific Ocean across the Pole and into the North Atlantic Ocean. In a sense the Arctic acts as a global "choke point" for calculating the freshwater budget of the world ocean. Part of this fresh water is converted to sea ice during the winter and exits the Arctic Ocean through Fram Strait; the remainder stays in liquid form and flows out both Fram Strait and the Canadian Archipelago.

This low-salinity Arctic outflow is delicately balanced with respect to the underlying water masses. Small changes in the amount and salinity of the outflow are sufficient to permit or restrain deep convection in the Greenland and Labrador Seas, which in turn affects the global thermohaline circulation. Recent observations indicate that deep water formation in the Greenland Sea experiences large interannual changes and in fact may have shut down completely in recent years.

Also changing is the exchange of deeper water masses between the Arctic and the Atlantic

Oceans through Fram Strait. Evidence from icebreaker and submarine cruises in the past several years indicates that since about 1990, Atlantic water types have expanded into parts of the Arctic Ocean that were previously dominated by waters from the Pacific Ocean. This will affect the formation and properties of polar water masses, since these are generally modified versions of Atlantic or Pacific types.

Uses of satellite data

POLES and retrospective satellite data. We want to utilize data—especially satellite data—to show the present state of the polar climate and how it works. The essential ingredient for progress in polar climate studies is data. Data are required for all aspects of modeling: setting of boundary and initial conditions, assimilation, and model testing. Data are required for diagnosing processes and for establishing a baseline against which to assess climate change.

At the inception of POLES in 1989, only one satellite data set was regarded as having any value for climate change research in polar regions—ice concentrations estimated from passive microwave radiometers—and even they were rarely used by modelers. None of the visible and thermal radiometer data or atmospheric sounding data were given much credence (except for radiances at the top of the atmosphere). This is because standard algorithms tend to break down in polar regions where the surface is as bright and cold as the clouds above. This means that the polar research community has been ignoring satellite retrievals of surface temperature and albedo, cloud fractions, and profiles of atmospheric temperature and moisture.

A major role of POLES is the systematic improvement and validation of satellite algorithms and data sets in polar regions. We have provided improved algorithms for surface temperature and albedo and cloud properties from AVHRR (advanced very high resolution radiometer); these are being implemented in the AVHRR Polar Pathfinder data set (http://polarbear.colorado.edu/) from 1982 to present. An alternative source of AVHRR data products is the ISCCP D1 data set (http://ISCCP.giss.NASA.gov/ISCCP.html) from the International Satellite Cloud Climatology Project. Similarly we have provided improvements for TOVS (TIROS-N operational vertical sounder) retrievals of polar atmospheric temperature and humidity profiles and polar surface stress parameters; these are being implemented in the TOVS Polar Pathfinder data set (http://psc.apl. washington.edu/pathp/pathp.html) for 1979 to present. (Also see the web page for all Polar Pathfinders: http://www-nsidc. colorado.edu/NASA/POLAR_PATHFINDERS/).

Our new and more efficient radiative transfer codes for computing surface and top-of-atmosphere radiative fluxes from these AVHRR and TOVS parameters show considerable promise for providing state-of-the-art surface flux fields resolving synoptic variability. Preliminary validations show that surface downwelling long-wave radiation from TOVS Polar Pathfinder has mean errors of -3 W/m^2 and a standard deviation of 23 W/m^2. Surface downwelling short-wave radiation from AVHRR has a bias of -4 W/m^2 and an rms error of 32 W/m^2. Further validation and intercomparison is underway, but these radiative flux data sets promise to be very useful.

Several of our investigators are working with EOS Instrument teams to improve algorithm performance in polar regions. J. Francis is working on polar algorithms with the CERES (Clouds and the Earth's Radiant Energy System) team. J. Key is a member of an advisory group for MODIS (moderate-resolution imaging spectroradiometer) for snow and ice products and is participating in a comparison of polar cloud detection algorithms for MODIS and ASTER. A. Schweiger attends AIRS (atmospheric infrared sounder) meetings to collaborate on polar algorithms on the basis of our experience with the TOVS 3I (French) algorithm. We are also actively pursuing ice tracking from passive microwave imagery as well as from SAR (synthetic aperture radar) as described next.

Radarsat Geophysical Processor System. POLES investigators have been active in planning for the Radarsat Geophysical Processor System (RGPS). RGPS is a sophisticated computer system that will take Radarsat SAR images of Arctic sea ice for input and create weekly, gridded geophysical products. A data acquisition plan has been formulated in which the entire Arctic Ocean is being imaged by Radarsat at weekly intervals, starting in the fall of 1996. RGPS will use these successive "Arctic snapshots" to track a dense array of tie points. RGPS products will be archived at the Alaska SAR Facility (ASF). RGPS development is being led by R. Kwok at the Jet Propulsion Laboratory. The fields of geophysical products include sea ice motion, the thickness distribution of new ice, and the backscatter history of the ice and will support studies, model improvements, and the development of climatologies of sea ice processes, thus meeting one of the milestones of the Polar Pro-

Information about RGPS is available at several linked web sites:

http://www.asf.alaska.edu/step/rgps.html

http://psc.apl.washington.edu/RGPS/rgps.html and

http://www-radar.jpl.nasa.gov/rgps/radarsat.html

cesses Program of the Earth Science Enterprise, which is to provide routine ice motion observations of the polar oceans by the late nineties.

Key achievements

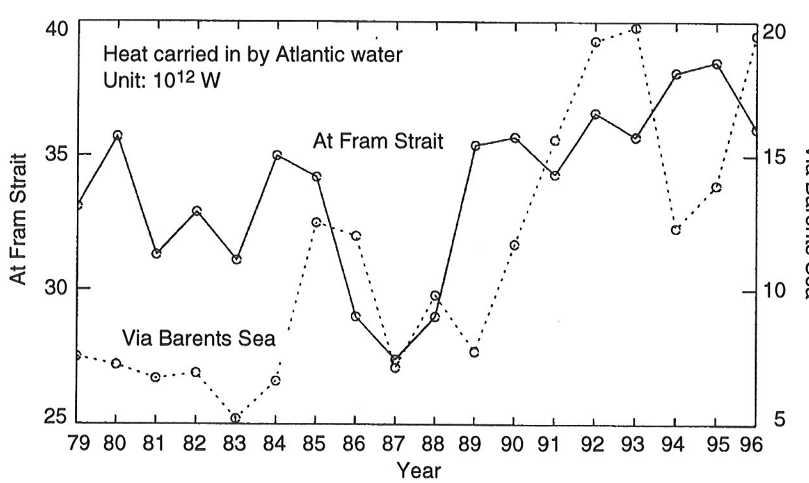
Surface radiative fluxes in models and global data sets

We have studied surface radiative fluxes in various data sets used to force ice models and have shown that there are unacceptably large discrepancies. Taking the World Climate Research Program (WCRP) goal of 10-W/m^2 accuracy in monthly means, we find, first, that the variation among the data sets examined is far greater than this value and, second, that even a 10-W/m^2 bias in downwelling fluxes causes sea ice thickness in models to vary by 20–50 cm (out of a mean thickness of about 3 m). The fluxes produced by POLES from TOVS and AVHRR Polar Pathfinder data are within the 10-W/m^2 requirement (in monthly averages) and will be an important standard for testing and improving sea ice and global climate models.

Trends in the Arctic Basin 2-m air temperature

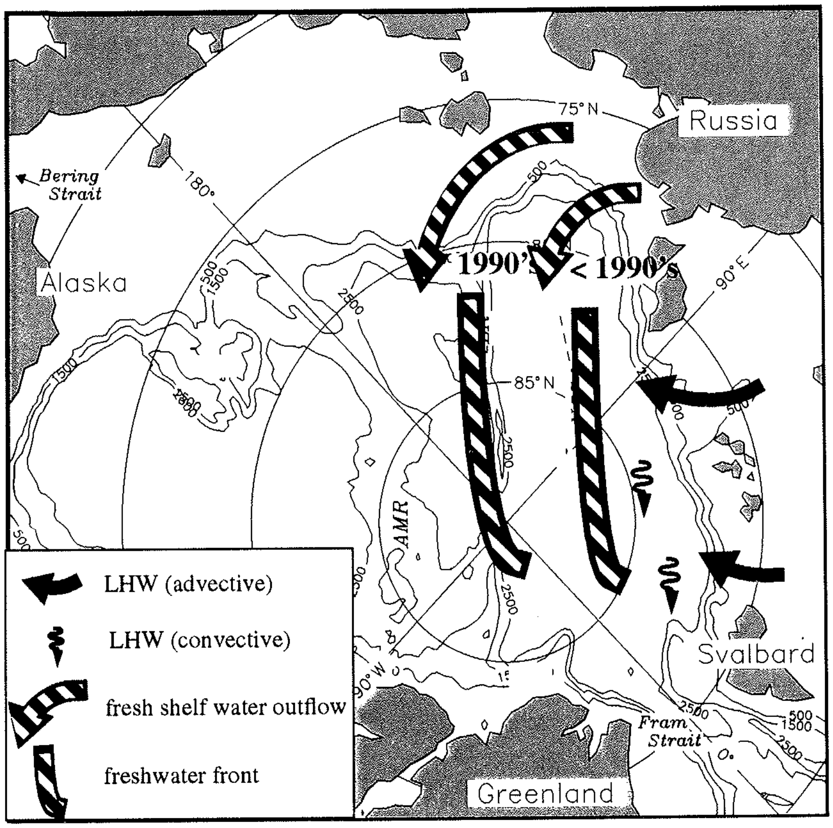
A new and more comprehensive temperature field of gridded 6-hourly, 2-m Arctic air temperatures for the years 1979–1995 is available on our web site. The fields were optimally interpolated from drifting buoys, manned Russian North Pole (NP) drifting ice stations, and coastal land weather stations. These data show mean seasonal temperatures consistent with other published estimates and the expected asymmetry between summer advance and retreat of the 0°C isotherm associated with the open water formation adjacent to the coasts. We also find good agreement between melt and freeze dates from the temperature record and published estimates derived from visible and passive microwave satellite data, which exhibit strong changes as the ice surface freezes or melts. We find a statistically significant warming in May and June of 0.8° and 0.4°C/decade, respectively, and a significant seasonal increase in summer of 0.2°C/decade. We find no significant trends in other seasons, in disagreement with an earlier report of cooling trends in other seasons deduced from radiosonde and dropsonde data. We are currently exploring relationships between Arctic temperatures, length of melt season, and interannual atmospheric variability expressed by such indices as the Arctic Oscillation.

Annual mean heat carried into the Arctic Ocean by Atlantic Water at Fram Strait and via the Barents Sea.

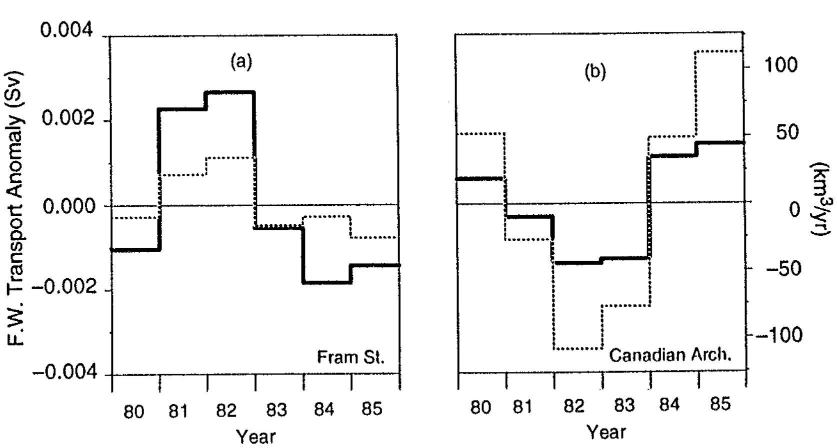


Atlantic water inflow into the Arctic—An NAO connection

A model analysis shows that Atlantic Water inflow to the Arctic Ocean has increased during the high North Atlantic Oscillation (NAO) phase in the early 1990s and that this increase is mainly via the Barents Sea. This is one of several significant changes in Arctic climate that have been observed in the late 1980s and 1990s as the NAO index has increased. During that period, there has been a decrease in sea level pressure in the Arctic, characterized by a weakening of the Beaufort high-pressure cell and a strengthening of the European sub-Arctic low-pressure cell and thus an altered wind circulation pattern. There has been a noticeable downward trend in the extent of Arctic sea ice, based on recent satellite data. Also, recent scientific cruises have revealed large-scale changes in the Arctic Ocean in the 1990s, with noticeable and persistent increases in temperature and salinity over a large area in the upper ocean. To get an insight into what is going on in the Arctic, we used the latest version of our coupled ice–ocean model to examine the behavior of the Arctic ice–ocean system in response to the recent changes in Arctic climate. The model shows that, starting about 1989, there has been a significant warming and salinification in the Arctic Ocean, in agreement with recent observations. The warming and salinification occur mainly in the upper ocean because of a sustained increase of Atlantic inflow both at Fram Strait and, most significantly, via the Barents Sea. The increased incoming warm and salty Atlantic water "flushes" out cold and fresh Arctic water, thus increasing the temperature and salinity of the upper ocean and resulting in more oceanic heat flux to the mixed layer and ice cover. The model also shows a continuing decrease in ice volume beginning in 1987.



Our view of the cold halocline layer formation and retreat. Lower halocline water (LHW, solid arrows) forms in the western and central Nansen Basin by a combination of advective (curved arrows) and convective (wavy arrows) processes, creating a deep winter mixed layer at freezing temperatures and a salinity of about 34.0–34.2. Injection of fresher shelf waters (striped arrows) into the Eurasian Basin occurs somewhere east of 90°E. The result is a year-round freshwater "cap" that creates a true cold halocline layer. The position of this injection point and the associated front that defines the boundary of fresh shelf-derived waters (striped curves) has shifted during the 1990s.



The anomaly of oceanic freshwater transport through Fram Strait and through the Canadian Archipelago. The solid line is our standard simulation, while the dashed line is a sensitivity study that uses a different advection scheme. Both show an out-of-phase relationship between freshwater outflows in the two channels.

Ocean data analysis: The 1990s vs. climatology

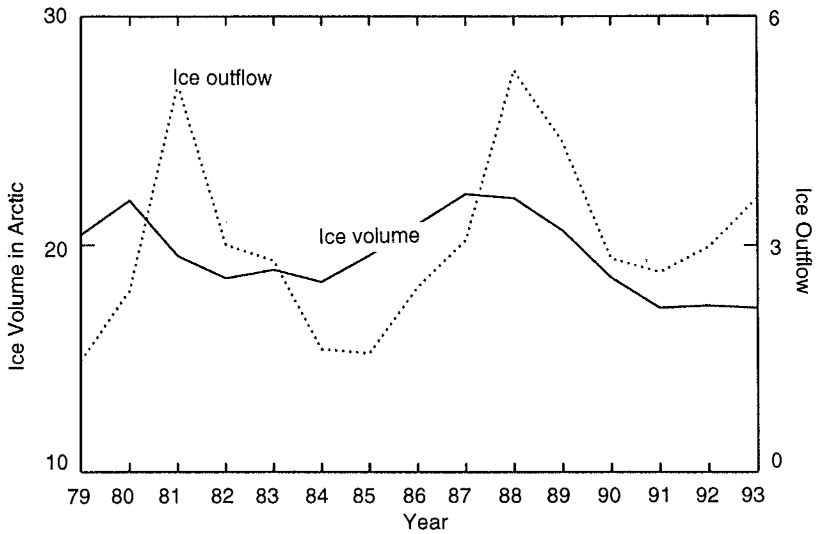
We have discovered a remarkable reduction in the extent of the cold halocline layer of the Arctic Ocean. This reduction has occurred over the course of the 1990s as observed in both icebreaker and submarine cruise data. The most recent observations discussed were collected during the spring 1995 Scientific Ice Expedition (SCICEX '95), the second in a series of scientific cruises to the Arctic Ocean aboard U.S. Navy nuclear submarines. Comparison with a new ocean climatology reveals that this change is larger than at any time over the previous 40 years. As a result, we expect a reduction in sea ice growth of about 30% as warm subsurface water mixes up to the surface. Specifically we find a retreat from the Amundsen Basin back into the Makarov Basin; the latter was the only region with a true cold halocline layer during SCICEX '95. Changes are also seen in other halocline types and in the Atlantic water layer heat content and depth.

The overall cause of water mass changes in the 1990s might have been a shift in the wind forcing and resulting sea ice motion during the late 1980s, which we speculate influenced the location where fresh shelf waters flow into the deeper basins of the Arctic Ocean.

Freshwater balance and ice mass balance of the Arctic Ocean

We have used a box model of the Arctic Ocean to compute the ice mass balance. Buoy motions and satellite ice concentrations are assimilated into the model. The motions and the salinity flux due to ice growth and melt are used to force a companion ocean model. We find large interannual and regional variations in ice thickness and in the ice export to the Greenland Sea. A unique numerical model of the upper Arctic Ocean has been developed to examine its freshwater budget. We find that roughly one third of the freshwater outflow exits through the Canadian Archipelago. Furthermore, the freshwater outflows through Fram Strait and through the Canadian Archipelago are out of phase, which should influence deep water formation in the northeast and northwest Atlantic Ocean, respectively. This result is very timely, given the present high state of interest in deep water formation sites and their variability. Ironically a major shift of the primary formation site from the Labrador Sea back to the Greenland Sea may have occurred just as an intensive field program in the Labrador Sea began.

We have examined the modeled response of



Fifteen-year record of sea ice volume (in 1000 km²) in the Arctic Ocean (solid line) and of the ice outflow (in 1000 km²/year) through Fram Strait.

Arctic sea ice to a 15-year record of interannual climate variability. Using a more realistic forcing and thickness distribution model than is common, we find that the Arctic ice outflow has much more interannual variability than found previously. The ice outflow peaks intermittently after quiescent periods of a few years with low ice outflow. This process is closely related to the intensity, location, and pattern of the Beaufort high and the European sub-Arctic low (which sits over the Norwegian, Barents, and Kara Seas). The total ice volume does not show dramatic change; however, the ice mass spatial distribution has changed considerably recently, such that a large area of open water/thin ice is seen both in observations and models. There is also large variability in the entire mass field and in the thickness of ice being flushed into Fram Strait. We plan to explore more fully the link to interannual and decadal climate variations in the northern hemisphere.

Data assimilation into sea ice models

We have used ice motion data to compute a seasonally varying air drag coefficient for ice models and have demonstrated that the ice thickness field is very sensitive to this parameter. This has allowed us to develop an ice model that assimilates ice velocity and ice concentration without producing unrealistic zones of intense deformation between regions with motion observations and those without.

Anticipated advances

There are several exciting areas in which we expect interesting new insights into polar processes, the role of the Arctic in global climate, and our ability to model these processes, both in global models and in more physically complete regional Arctic models.

Clouds, surface properties, and surface fluxes from AVHRR and TOVS

Our goal is to produce multiyear data sets of Arctic surface and cloud properties, atmospheric profiles, and surface and top-of-atmosphere radiative fluxes. We are testing data products as they become available with the goal of having 14-year (AVHRR) and 18-year (TOVS) data sets available in 1999. We have identified weaknesses in the AVHRR retrieval algorithms in early analyses of ISCCP and AVHRR Polar Pathfinder (APP) products. Low sun angles and fine-scale cloud structure are two causes of error. The APP algorithms have been modified to avoid these errors.

The surface and top-of-atmosphere radiative flux data set that A. Schweiger and J. Key produced in 1994 using the ISCCP C2 (C indicates the third revision, the 2 indicates monthly fields) cloud product is being updated using the reprocessed ISCCP D1 (the 1 indicates 3-hourly) product with its improved polar algorithm. This incorporates some of the thinking that went into our CASPR (Cloud and Surface Parameter Retrieval System) algorithm. We believe it is a significant improvement on the C2 data set. At present only six full years of ISCCP D1 data are available: 1986 and 1989–1993. It is not known when the entire 1983–1996 data set will be available. Our plans are to continue reprocessing the ISCCP cloud product as it becomes available to compute surface and top-of-atmosphere radiative fluxes, and the cloud radiative effect ("forcing").

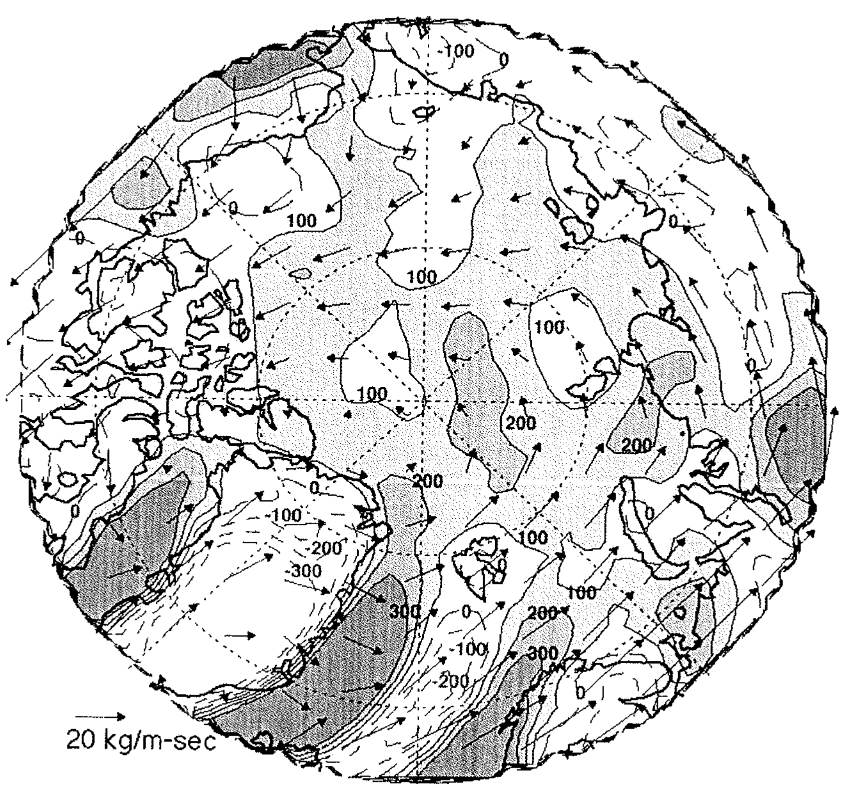
The TOVS algorithm ingests temperature, moisture, and cloud information from TOVS retrievals and infers additional cloud information from the brightness temperatures themselves. Fluxes are then computed using the Streamer radiative transfer model. The next step is to apply the method to all 18 years of TOVS Polar Pathfinder data that will soon be available, thereby generating the first data set of its kind. To accelerate the radiation calculations, we are using a neural network.

Our plans are to continue assessing errors in the estimates of TOVS- and AVHRR-derived temperature and albedo and radiation data products by comparing them with in-situ data from CEAREX (1988), LEADEX (1992), the Arctic Ocean cross section (1996), BASE (1994), SHEBA, and NP stations.

The combination of these radiation and cloud data sets, along with advection from numerical weather prediction model re-analyses, will provide a tremendous opportunity to analyze interrelationships between lateral energy advection, surface radiative fluxes, and cloud formation. As POLES algorithms are becoming solidified and data sets generated, POLES efforts are being directed more toward analyses, especially within the context of developing parameterizations and understanding climate change processes.

Arctic atmosphere: Horizontal energy and moisture advection

The advection of energy into the Arctic from lower latitudes, and the deposition of that energy within the Arctic, plays a dominant role in the Arctic climate, as well as providing the primary link between the Arctic and the global climate system. Previous studies have analyzed energy transfer into the Arctic using rawinsondes and re-analysis products from both National Center for Environmental Prediction (NCEP) and European Centre for Medium-Range Weather Forecasting (ECMWF) numerical weather prediction models. We are analyzing poleward fluxes of heat and moisture using polar-orbiting satellite data since 1978. Temperature and moisture profiles from the TOVS Polar Pathfinder project and winds from the NCEP re-analysis provide daily advective fluxes of heat and moisture with spatial resolution not available from rawinsonde data. The divergence of these fluxes (plus a small term from the change in water stored in the atmosphere) gives as a residual the net exchange of moisture with the surface: precipitation minus evaporation, or P–E.



Moisture balance of the Arctic, from NCEP winds and TOVS PP moisture fields, averaged for 1985–1990. The vectors are moisture transport. The contours are of P–E in mm/year, computed from flux divergence. Darker is more positive. The North Pole is at the center; the Greenwich meridian is to the bottom. Coastlines are bold. (Values over Greenland are not corrected for surface elevation and are not valid.)

We plan to compute evaporation independently from ice concentration and surface temperature and wind data. The resulting precipitation estimates (by adding E to P–E), if shown to be valid, would be the first spatially and temporally varying estimate of precipitation for the Arctic Ocean. As snowfall rate or snow depth is a major data void in sea ice modeling and has a large impact on ice thickness and growth, these estimates would be extremely valuable.

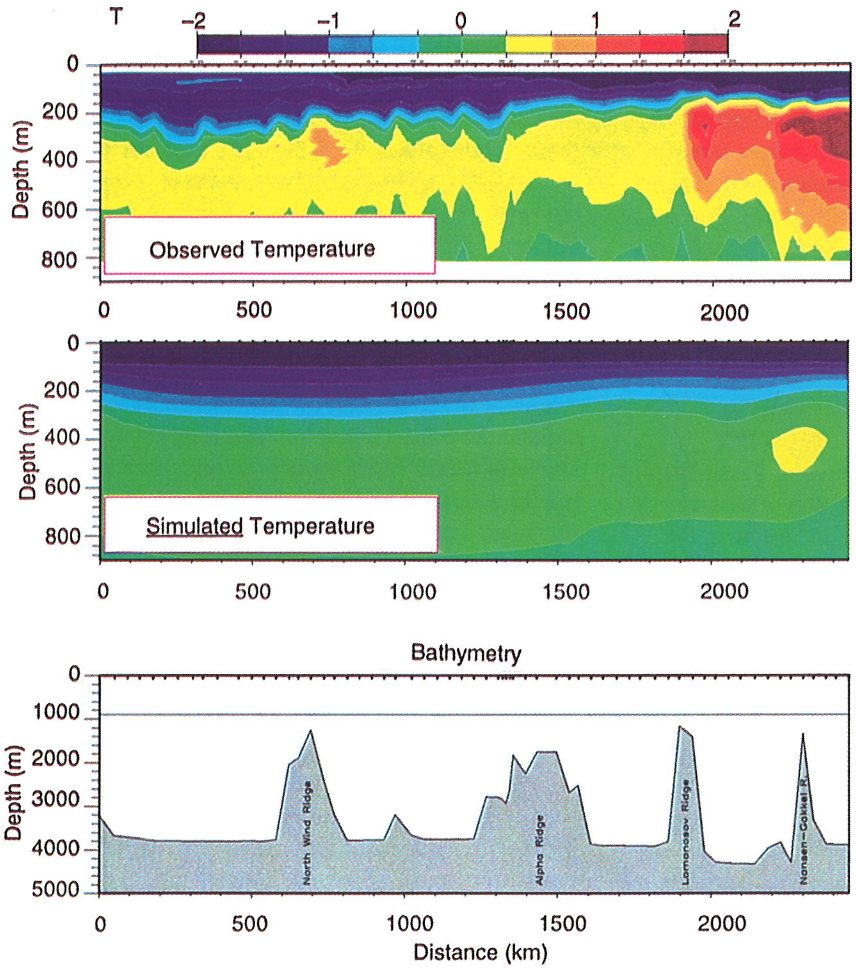
In the near future we will complete the analysis of moisture and heat transport into the Arctic for the 18-year TOVS Polar Pathfinder period. We will fully analyze the interannual variability of the atmospheric heat and moisture budgets and the significant pathways and deposition sites of energy and moisture in the Arctic. We will compute an atmospheric heat budget and see how well it agrees with independent surface heat flux estimates.

Ocean model validation

We have begun a comparison between observed data (1990s and climatologies) and model output. We find large differences that are dependent on uncertain model parameters. The discrepancy is not so large when the model is not continuously forced back to the climatological observations, a common numerical technique. This is just one example of how we are finding that model validation using these new observations can be quite useful in testing various parameterizations and model assumptions. We will continue to examine these differences in a quantitative manner in order to test the ocean model. A final suite of model parameterizations, optimized to the observations, is our goal. We are collaborating with modelers at the Naval Postgraduate School and the National Center for Atmospheric Research on these studies.

Ice thickness: Comparison of submarine observations and models

How well do sea ice models represent ice thickness? How good are ice thicknesses computed in GCMs? Would models recognize it if the sea ice



Observed and simulated temperatures across the Arctic Ocean from just off Barrow, Alaska, on the left to 250 km north of Franz Josef Land on the right. The top panel shows data taken during SCICEX '95, where the warm subsurface layer at several hundred meters deep marks the Atlantic Water layer. Particularly warm cores are observed over bathymetric ridges. The model simulation is much too cold, mostly because the model solution is restored back toward the (colder) climatology at every time step. Removal of this "climate restoring" creates a better simulation, but the solution tends to drift slowly over time. Poor atmospheric forcing data (that is, surface fluxes) may also play a role.

cover were getting unusually thin and even were on the verge of disappearing? Superlative answers can be obtained by comparing model output to the 20 years of historical submarine ice thickness data soon to be released. We have begun a comparison between a model and the available submarine data from just one month: September 1993 on a SCICEX mission. From the model we extract the data along the same track and at the same times (over a period of about a week), so that the model data subset is as comparable as possible to the observational data set.

Comparing only the modeled and observed data from the 1993 track, the means differ by less than 10% and the standard deviations are 1.0 m (model) and 0.8 m (submarine data), so the model has realistic statistics. However, the model is only somewhat correlated with the observations. Working now with the data we have from submarine cruises in 1992, 1993, 1996, 1997, and soon, 1998, and soon with the 20 years of historical submarine data, we will make more thorough comparisons between real and modeled thickness. With this new standard we can test models and learn how to improve the model physics and their thermodynamic and momentum forcing data in ways that improve their agreement with observations. Such tests will provide a crucial measure of performance for sea ice models at many levels of physical sophistication.

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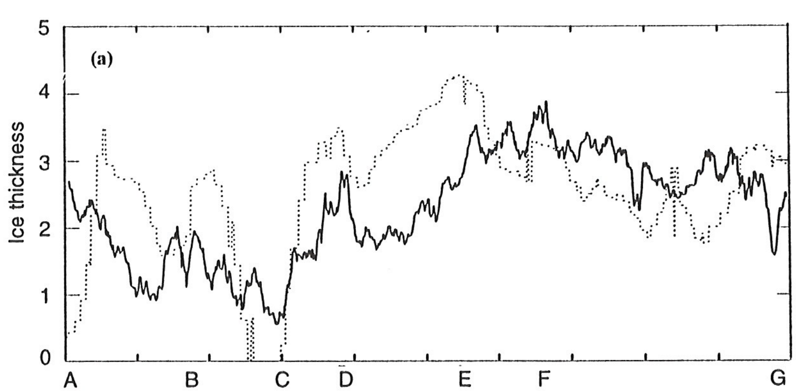

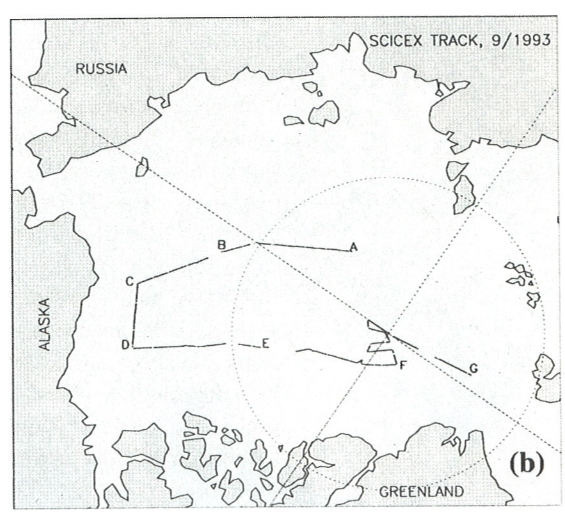

Comparison between mean ice thickness from an ice model (dashed line in part a) and that observed from a submarine (solid line in a). Both modeled and observed data are from the time (September 1993) and location of the submarine track shown in (b). Positions along the track are shown in both figures by capital letters.

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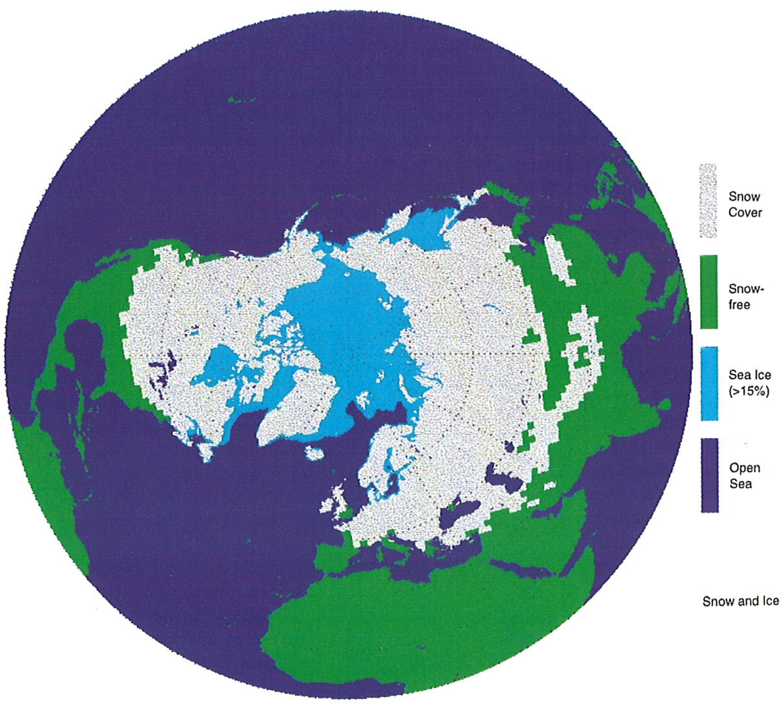
Cryospheric Research and Data Products from the National Snow and Ice Data Center

This report was prepared by R.G. Barry, R.L. Armstrong, J.A. Maslanik, and T.A. Scambos, Cryospheric and Polar Processes Division, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder.

The National Snow and Ice Data Center (NSIDC) and the World Data Center-A (WDC-A) for Glaciology at the University of Colorado at Boulder are operated through a NOAA–University cooperative agreement under the auspices of the National Geophysical Data Center, which is part of the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service (NESDIS). The center also operates the Snow and Ice Distributed Active Archive Center (DAAC) for the Earth Observation System Data and Information System (EOSDIS). Its mission is to "make fundamental contributions to cryospheric science" and to "excel in managing data and disseminating information in order to advance understanding of the Earth system." The WDC-A for Glaciology was transferred with NOAA support to the University of Colorado from the U.S. Geological Survey in Tacoma, Washington, in 1976, and the NSIDC title was established through NOAA in 1982. Multi-agency funding of NSIDC began in 1983, and the DAAC was initiated in 1991 with NASA EOSDIS support to serve the snow and ice community of EOSDIS and MTPE (Mission to Planet Earth, now renamed Earth System Enterprise).



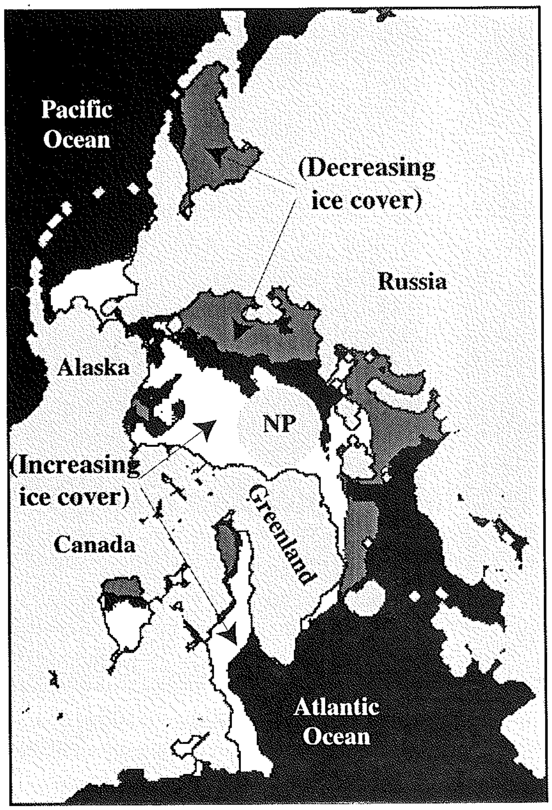
Northen hemisphere snow and ice extent for January 8–14, 1979, the week of maximum snow extent (52.578 million km) for the time period 1978-1995. The complete data set is available from NSIDC (http://www-nsidc.colorado.edu/).

The DAAC data holdings comprise over 50 data sets. The majority are satellite-derived, and the others are in-situ validation data. They total 3.7 TB, of which 3 TB are polar AVHRR (advanced very high resolution radiometer) data.

The principal data sets include:

- Gridded brightness temperatures for the polar regions from SMMR (scanning multichannel microwave radiometer) and SSM/I (special sensor microwave imager) (1978–ongoing) and derived sea ice concentration grids;
- Radar altimetry data for the Greenland and Antarctic ice sheets and a digital synthetic aperture radar (SAR) mosaic and elevation map of Greenland;
- Rawinsonde data from the late 1940s to mid-1996 for land stations north of 65°N and derived gridded water vapor characteristics;
- TOVS (TIROS operational vertical sounder) Pathfinder atmospheric grids for the Arctic;
- AVHRR 1-km data grids for the Antarctic since April 1992 and the Arctic since August 1993;
- Northern hemisphere EASE-Grid (Equal Area Scalable Earth Grid) weekly snow cover and sea ice extent;
- Historical daily snow depth data for 284 stations in the former Soviet Union and snow course records for 1345 sites in the FSU for 1966–1990;
- Russian sea ice equal-area gridded charts for the Arctic for 1953–1990; and
- Sea ice draft data from U.S. Navy SCICEX submarine cruises since 1996.

During 1998–1999 the completed Polar Pathfinder data sets from AVHRR, SMMR-SSM/I, and TOVS will become available from the NSIDC DAAC, together with MODIS (moderate resolution imaging spectroradiometer) snow and sea ice



Trends in northern hemisphere ice concentration for 1979–1995. (Increasing ice = white; decreasing ice = dark gray).

products from the EOS AM platform (AM refers to the morning ascending node).

NSIDC distributes data on CD-ROM and tape media and via ftp. Its data catalog and other information services are described at www-nsidc. colorado. edu. The center publishes a quarterly newsletter called *NSIDC Notes,* which reports on new data releases and related data activities, as well as an annual report and glaciological data reports. NSIDC publishes the annual *DAAC Yearbook*, which presents science highlights based on studies using DAAC data.

Cryospheric research highlights

Arctic sea ice: Regional trends and variability

Hemispheric averages of sea ice extent (ocean area with at least 15% ice) suggest a general downward trend in ice cover for 1979–1996, as mapped using passive microwave satellite imagery. However, the areas with a net decrease in ice cover are confined mainly to the Eurasian Arctic and are partially offset by regions with increasing ice extent or fractional coverage (ice concentration).

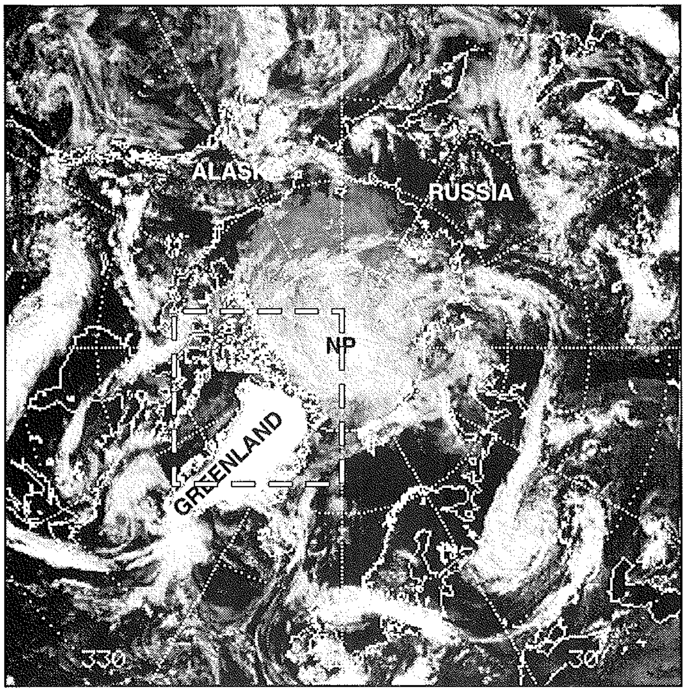
In the Arctic Ocean proper, the sea ice trend is dominated by relatively large reductions in summer ice extent, as well as increased variability in recent years, particularly since 1989. The regional nature of the sea ice trends indicates linkages to synoptic-scale atmospheric circulation rather than to a global increase in air temperatures and are consistent with trends in other climate observations. In particular, the reductions in ice extent in the Siberian Arctic are related in part to an increase in cyclonic activity over the Arctic Ocean since 1989, which has occurred in conjunction with, or perhaps as a modification of, the positive mode of the North Atlantic Oscillation that has persisted in recent years.

Ice model simulations for 1985–1993 suggest that, after mid-1988, the total ice thickness in the Arctic Ocean may have decreased in conjunction with the observed ice and atmosphere trends. The simulated decrease is consistent with the observed ice transport patterns and agrees with the ice model's estimate of ice thickness and age. The greater variability of the observed ice extent is also consistent with a thinner ice pack, which can respond more readily to changes in air temperatures or wind direction. Also consistent with this are apparent reductions in ice fraction in the central Arctic in the summer of 1996. The magnitude of these reductions in 1996 and the physical appearance of the pack ice are more typical of regions covered by seasonal ice cover rather than the perennial, thick, high-concentration ice pack typical of the interior Arctic.

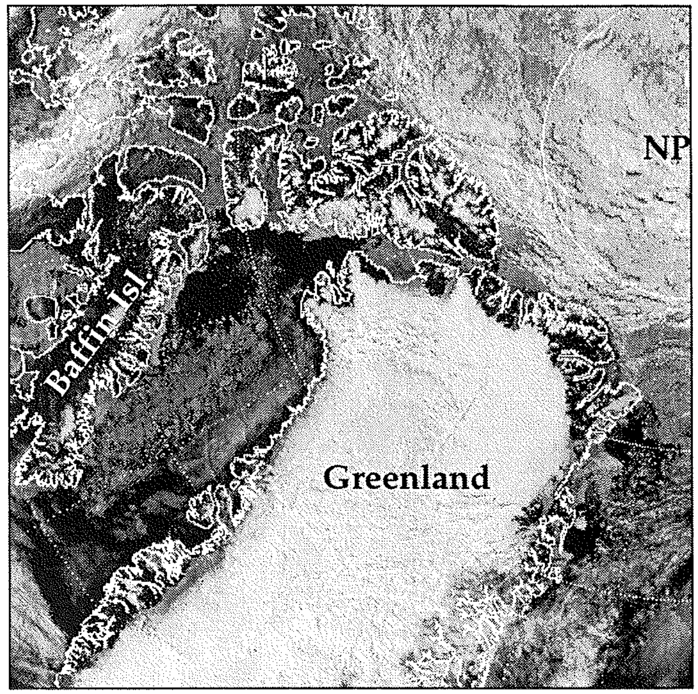
Satellite products for studying polar ice transport and weather patterns

As part of the NOAA/NASA Pathfinder effort, new data sets are being generated that combine information from several sources to support long-term climate studies. The goal of the AVHRR-based Polar Pathfinder is to produce a consistent and uniform suite of remotely sensed products that describe key components of the polar climate system: surface temperature, albedo, cloud fraction, and ice transport.

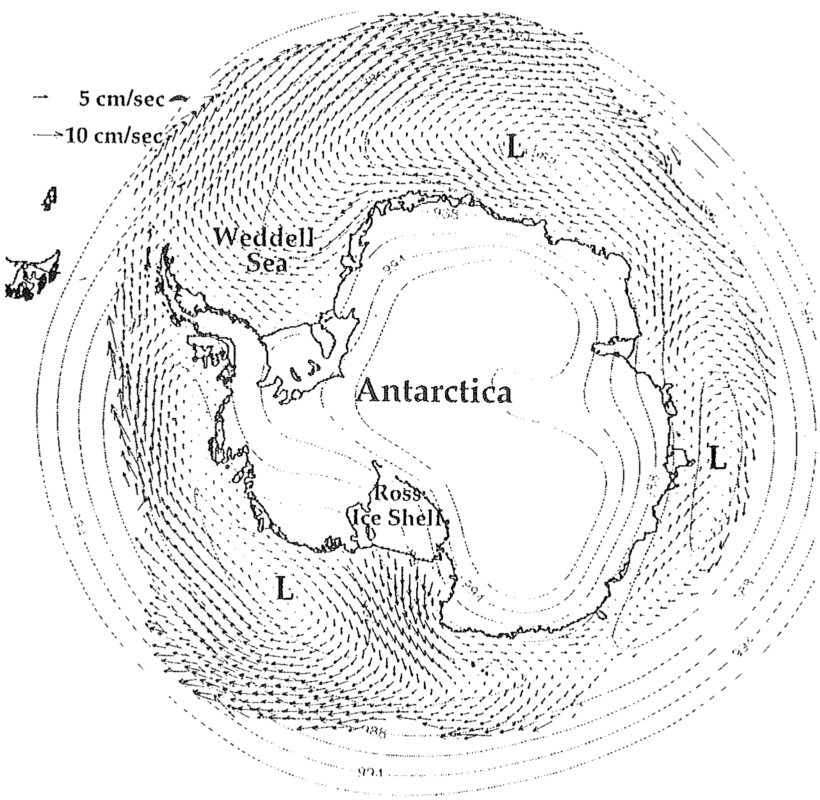
The AVHRR-based Polar Pathfinder (APP) project is generating multi-year, gridded products for the northern and southern hemispheres (approximately 50° latitude to the poles) using data from eight satellites for 1983–1996 at grid cell sizes ranging from 1.25 to 25 km. The resulting data sets provide previously unseen views of the variability of the polar regions over time and space. Parameters such as albedo and skin temperature can be analyzed individually or in combination with other Pathfinder products and climate



Composite of AVHRR-derived broad-band albedo for the northern hemisphere on 17 July 1987 with 25- × 25-km pixels (from the AVHRR Polar Pathfinder project).



Subset of the albedo composite to the left at the standard AVHRR Polar Pathfinder resolution of 5 km. These composites are being produced for 1981–1998 as part of the Pathfinder effort.



SSM/I-derived sea ice mean velocities for 1988–1994. Superimposed on the ice velocity vectors are contours of mean sea level pressure for the same period. Note the correspondence between ice drift patterns and the locations of low pressure systems ("L"). Daily grids of ice motion are a standard product of the AVHRR Polar Pathfinder.

data sets. For the Antarctic the Pathfinder data are providing the first comprehensive view of ice transport patterns throughout the Southern Ocean. The APP exemplifies the Earth Observing System's integrated, multi-sensor approach to global climate monitoring by providing the first polar-wide suite of products that help describe the growth, melt, and movement of sea ice. Combinations of these remotely sensed products with climate models should yield new insights into the key mechanisms controlling the ice–ocean–atmosphere system.

Passive microwave remote sensing for monitoring global snow cover

The extent and variability of seasonal snow cover is recognized as an important parameter in climate and hydrologic systems. At its average maximum extent, snow covers about 40% of the land surface of the northern hemisphere and is the single greatest source of albedo fluctuations, both in magnitude and extent. Trends in snow cover are also expected to serve as an indicator of global climatic changes. Up to now, analyses have focused primarily on trends in northern hemisphere snow extent based mostly on monthly averages using charts derived from visible-wavelength data or station data for selected regions. Passive microwave data from satellites allow us to monitor temporal and spatial variations in snow cover on the global scale, avoiding the problems of cloud cover and polar night, and to compute snow depth and snow water equivalent.

NSIDC is evaluating the accuracy of existing passive microwave snow cover algorithms, as well as developing new sets of algorithms that will be appropriate for application at the global scale. The product will be a global time series of snow water equivalent based on the SMMR and SSM/I data sets for the period 1978–1998. In our initial passive microwave algorithm validation effort we have compared the average monthly snow extent from the northern hemisphere NOAA–NESDIS weekly snow charts, a visible-spectrum (primarily AVHRR and GOES [Geostationary Operational Environmental Satellite]) satellite data product, with that derived from passive microwave data. The common gridding scheme being used to compare these two data sets is the NSIDC EASE-Grid, described below. For most months of the year, the two methods compare favorably. However, during October, November, and December, the passive microwave algorithms appear to significantly underestimate the snow extent in certain regions. This difference may result from either soil conditions beneath shallow snow or the inability of the passive microwave to detect shallow snow, or both. A focused effort to determine the cause of this difference and to adjust passive microwave algorithms is underway within the context of activities described below.

The general validation work is being undertaken in collaboration with an ad-hoc working group on snow cover algorithms convened by Richard Armstrong. On August 25–27, 1997, NSIDC hosted the initial meeting of this group, which was composed of 12 invited participants representing five U.S. government agencies, one Canadian government agency, and five U.S. universities. The purpose of the meeting was to share ideas on various methods to develop and test snow cover algorithms and to promote collaboration in an effort to more efficiently solve the problems associated with these research tasks in a synergistic fashion. All participants supported the concept of collaboration, including the sharing of data and preliminary research results. Several action items defined specific tasks to be undertaken by individual participants that will benefit the group in general. Interim results of this collaboration are posted on the group's web site, which is maintained by NSIDC and is currently available to working group participants. A second meeting was held in Seattle in July 1998 to coincide with the International Geosciences and Remote Sensing Symposium.

Specific algorithm validation tasks are being undertaken in collaboration with Christian Maetzler and Daniel Hiltbrunner (Applied Physics Institute, University of Bern, Switzerland) and with A.T.C. Chang (NASA-Goddard Space Flight Center) in support of the development and validation of a global snow extent and snow water equivalent algorithm for the NASDA (National Space Development Agency of Japan) ADEOS-AMSR (advanced microwave scanning radiometer).

Standard Earth grid

A task fundamental to advancing global change research is the availability of a standard reference system for direct digital comparison and the use of remote sensing data sets on varying spatial and temporal scales. The availability of a standard gridding scheme is essential for systematic time-series studies. Such a scheme also supports the direct comparison and validation of different remote sensing algorithms through digital comparison with surface station and other ancillary data sets that have been processed into the common grid.

The standard gridding scheme being applied in the passive microwave (and other remote sensing) projects at NSIDC is the EASE-Grid. In the specific case of SSM/I data, EASE-Grid provides an optimal Earth grid format that is between swath data (for example, one file per orbit) and an averaged (time and space) daily or multi-day product with its associated reduction in precision. The interpolation scheme to move from swath coordinates to Earth-gridded coordinates is based on the Backus–Gilbert method, and the net effect is as if the satellite radiometer itself had been pointing at the center of each grid cell.

The NOAA/NASA Pathfinder Program Level 3 EASE-Grid brightness temperatures were the first remote sensing products to benefit from EASE-Grid. This data set includes both the SMMR data (1978–1987) and the SSM/I data (1987–1997), providing a 20-year time series of satellite passive microwave data in a common format.

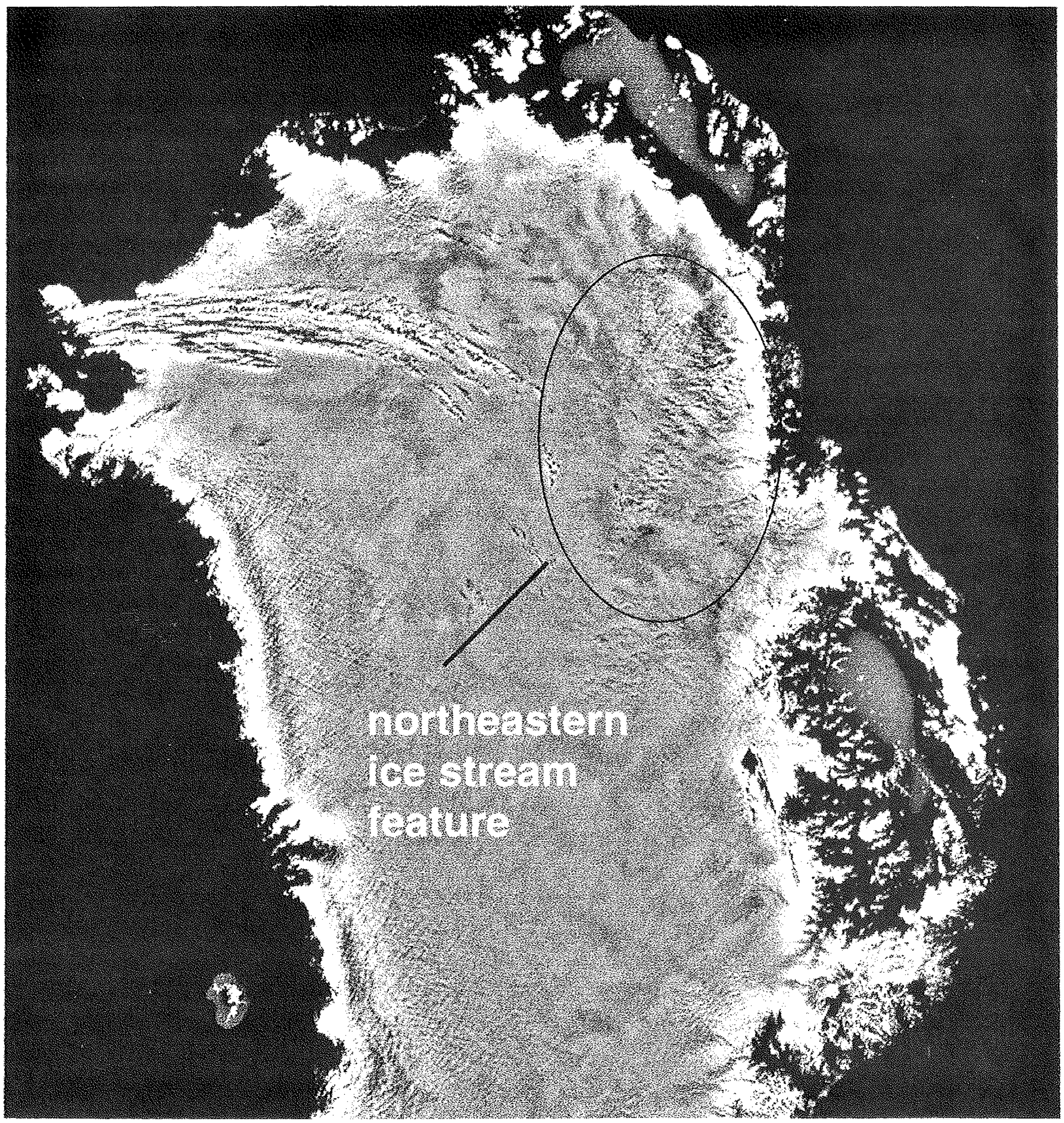
Although the specific method used to interpolate from satellite swath coordinates to a fixed Earth grid will be unique to each sensor, the fundamental gridding and projection scheme of the EASE-Grid provides the basis for a standard gridding method. For example, the EASE-Grid is being used for other products being distributed by the NASA Polar Pathfinder Program, such as AVHRR and TOVS. It is also being used for various environmental data sets being distributed by NSIDC, including northern hemisphere EASE-Grid weekly snow cover and sea ice extent for 1978–1996, Arctic and Antarctic Research Institute 10-day Arctic Ocean EASE-Grid sea ice observations, and Arctic water vapor characteristics from rawinsondes.

Arctic AVHRR data at NSIDC and their research applications

NSIDC has collected a time series of AVHRR data at 1-km resolution from several high-latitude stations surrounding the Arctic basin, providing almost complete coverage of the Arctic Ocean, Alaska, and Greenland over the last four years. At this resolution the data are highly valuable for process studies at the regional level and have been used in that capacity by researchers, both within and outside NSIDC.

Within NSIDC the data have been used for mapping dynamic portions of the Greenland ice sheet and enhancing digital elevation models (DEMs) of selected areas using photoclinometry. In particular, the focus has been the ice stream in northeastern Greenland. AVHRR images were used to support more-detailed radar data in terms of mapping the extent and morphology of the ice stream. It was also used to enhance the regional DEM of the area (provided by the Danish geodetic

Greenland ice sheet imaged with 1-km AVHRR (discovery image for the northeastern feature).



survey, KMS) using photoclinometry. This enhancement provided for the first time a quantitative map of the relief of surface features within the ice stream and strongly suggested (along with balance velocity maps of the area) that, unlike Jacobshaven, the northeast Greenland feature is in general melted at the bed. The AVHRR data of the area has appeared in numerous publications by Kwok, Fahnestock, Joughin, and Scambos.

The data have been requested by numerous outside groups, primarily for regional studies of sea ice and snow cover. A study by Ron Lindsay used AVHRR to observe the formation and summer break-up of sea ice near the river deltas of the north coast of eastern Siberia. The question addressed was whether the local freshwater input by the rivers had a noticeable effect on the timing and structure of freeze-up and melting. More extensive studies, by several research groups, focused on the Northeast Water polyna of Baffin Bay, in which 1-km AVHRR data were used to monitor the formation and extent of the polyna over several summer seasons. The timing and duration of the polyna's opening have been changing over the last few years. One-kilometer AVHRR data provide an accurate assessment of this timing remotely. Publications are in preparation by John Heinrichs (Cooperative Institute for Research in Environmental Sciences) on this subject. The data are also being used to validate other sensor data, such as SSM/I and the Russian Okean. One such use has been made by David Douglas, who is acquiring NSIDC AVHRR data to attempt to validate hard-copy maps of sea ice extent made by Russian meteorologists using Okean data.

One-kilometer AVHRR is an excellent means for determining sea ice motion, as was demonstrated by Chuck Fowler (University of Colorado). AVHRR was used to map ice motions over an 18-month period in the central Arctic. The motion field was validated with both buoy data (as part of the study) and SAR imagery (as part of the development of the Radarsat Geophysical Processing System). Currently 4-km AVHRR data are being used along with 85-GHz SSM/I data, buoy drift data, and wind information to generate a blended ice motion product. The upcoming Pathfinder products will augment this with 1-km derived ice motions over the entire Arctic basin.

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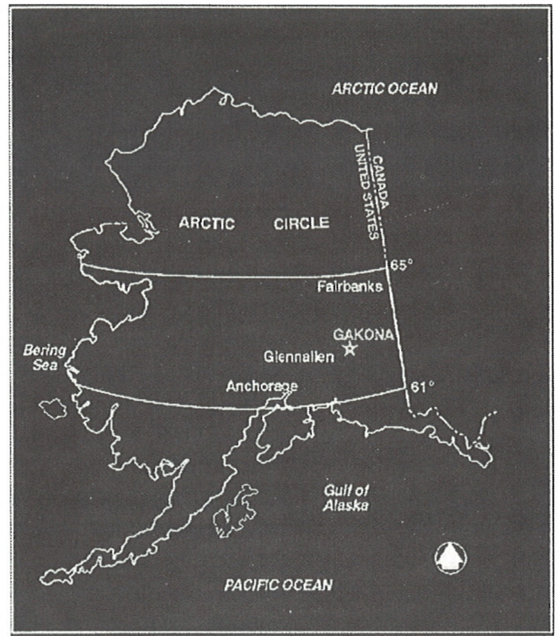
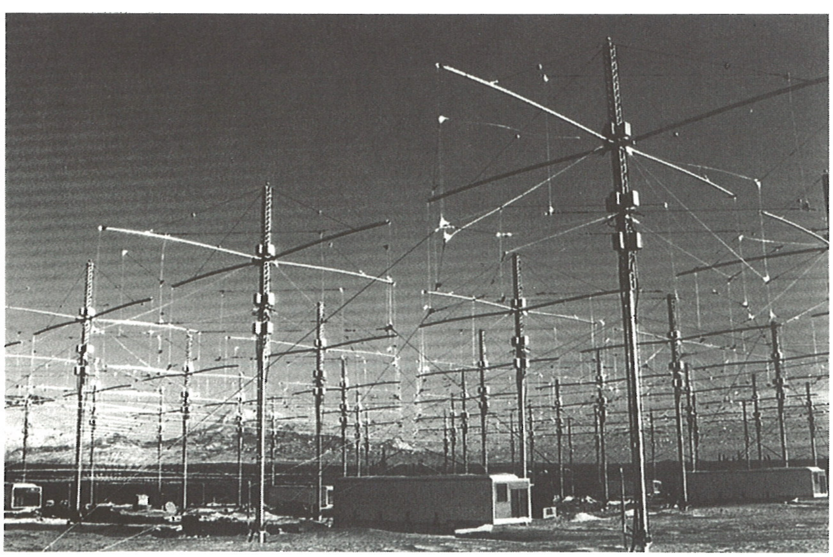
High Frequency Active Auroral Research Program

This report was prepared by P.A. Kossey and J.L. Heckscher of the Air Force Research Laboratory, Hanscom AFB, MA; H.C. Carlson of the Air Force Office of Scientific Research, Washington, DC; and E.J. Kennedy of the Naval Research Laboratory, Washington, DC.

A major facility for conducting experimental radio science research is under development in Gakona, Alaska, as part of the High Frequency Active Auroral Research Program (HAARP), jointly managed by the Air Force Research Laboratory and the Office of Naval Research. A key objective of the program is to identify and characterize the physical processes that can be initiated in the atmosphere, ionosphere, and space via interactions with high-power radio waves. Among these are plasma instabilities and turbulence; electron acceleration, including the production of optical and infrared (IR) emissions; the generation, maintenance and/or suppression of ionization structures aligned along the Earth's magnetic field; the modulation of currents in the ionosphere, producing virtual antennas in space to generate ULF/ELF/VLF radio waves; and the production of stimulated electromagnetic emissions (SEE). The efficiencies that can be obtained in initiating, maintaining, and controlling such processes and techniques to excite selected (individual) processes, or to suppress unwanted ones, are also research areas of increasing interest. Other program objectives include experimental research to assess the potential for exploiting this emerging ionospheric technology for new radio wave system applications and the use of the facility to support collaborative research programs such as those associated with global change and the National Science Foundation's Space Weather Initiative. To provide the experimental capabilities required to meet its objectives, the HAARP Gakona facility includes a powerful, phased-array, high-frequency (HF) transmitter and an extensive complement of radio-frequency and optical diagnostic instruments.



Location of the HAARP facility.



The present 960-kW, 48-element, HF antenna array at Gakona. The planned full array will have 180 elements and will radiate 3.6 MW.

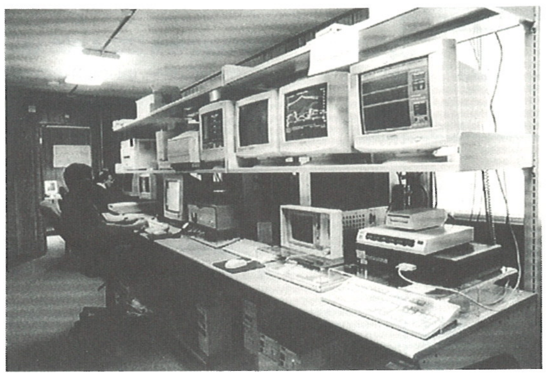
HF transmitter and diagnostic instruments

Currently the HF transmitter/antenna consists of 48 antenna elements arranged as a rectangular array of eight columns by six rows, with a radiated power of 960 kW. Plans are to increase this to a 180-element system having a radiated power of 3.6 MW. In addition, the transmitter has a number of advanced features, making it an especially flexible and attractive instrument for the experimental research envisioned under the program. These include an array bandwidth of approximately two

HAARP diagnostic instruments

• HF vertical incidence sounder	• HF SEE receivers
• ELF/VLF/LF receivers	• Magnetometer
• VHF (30-MHz) riometer	• Imaging riometer
• VHF (50-MHz) radar	• IR photometer
• HF (28-MHz) radar	• Spectrum monitor
• UHF incoherent scatter radar*	• Optical imager
• UHF scintillation monitors	• Rayleigh LIDAR

* Not yet available.



Present diagnostic instrument displays at the HAARP facility. A larger area, including additional instrument displays, will be available when a modern site operations center is completed.

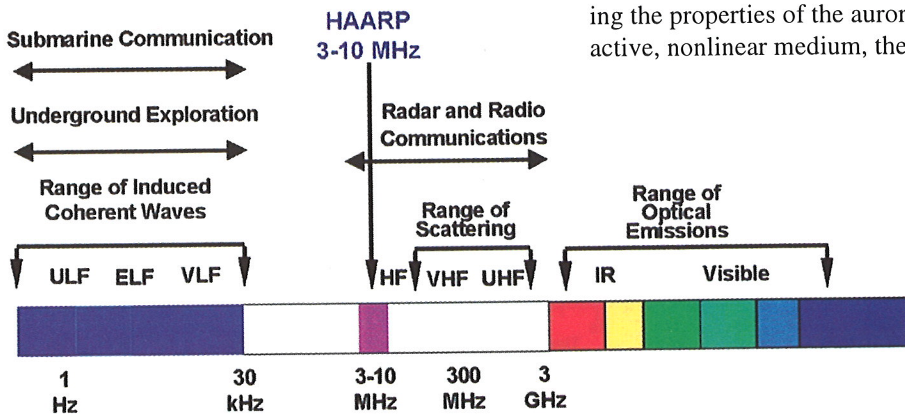
octaves (2.8–10 MHz), a very wide and rapid scanning capability (±30° in all directions from the zenith in 10-μs increments), the capability for any cross/circular or linear polarization, flexible control of transmitted waveforms, and the capability to operate at two frequencies simultaneously.

The suite of on-site and off-site diagnostic instruments for the facility is extensive and diverse and is important in monitoring the local geophysical and electromagnetic background. They serve an essential role during active experiments employing the HF transmitter, providing knowledge of ionospheric conditions prior to, during, and after its operation. Data collected from the instruments are processed and displayed at the site and can be provided in real time to other researchers via the Internet. Many of the instruments are important diagnostic tools in their own right, having the capability to observe naturally occurring ionospheric processes when active research using the HF transmitter is not being conducted. For example, monitoring the outputs of these instruments on a day-to-day basis provides insight into the correlation between naturally occurring geophysical processes and radio wave propagation conditions.

Additional information about the HAARP program and its Gakona, Alaska, facility can be found on the Internet at <http://www.haarp.alaska.edu> or by contacting the HAARP Program Office, AFRL/VSBI, Hanscom Air Force Base, MA 01731.

Remote sensing research opportunities

The HAARP facility, currently under development in Alaska, is the outgrowth of almost 40 years of "ionospheric heating" research. A wealth of experimental studies conducted at ionospheric heating installations, such as the ones in Arecibo, Puerto Rico; Tromso, Norway; Fairbanks, Alaska; and several installations in the former Soviet Union, have brought the basic understanding of the physics and the phenomenology of HF interactions in the ionosphere to a new plateau. The advanced features and flexibility of the HAARP HF transmitter will enable it to build on these achievements in important areas of remote sensing of the upper atmosphere, ionosphere, and magnetosphere. The primary energy of the HAARP transmitter can be radiated at any selected frequency between 2.8 and 10 MHz. By matching the radiating frequency to the ionospheric electron density profile, the radiated energy can be deposited selectively at altitudes between 70 and 90 km (known as the D/E regions of the ionosphere) and between 200 and 300 km and higher (known as the F region), or it can escape into space and interact with the magnetosphere. The location of the powerful HAARP transmitter underneath the auroral electrodynamic circuit, coupled with its operating flexibility, provide a novel and unique broad-band remote sensing resource. By exploiting the properties of the auroral ionosphere, as an active, nonlinear medium, the primary energy of

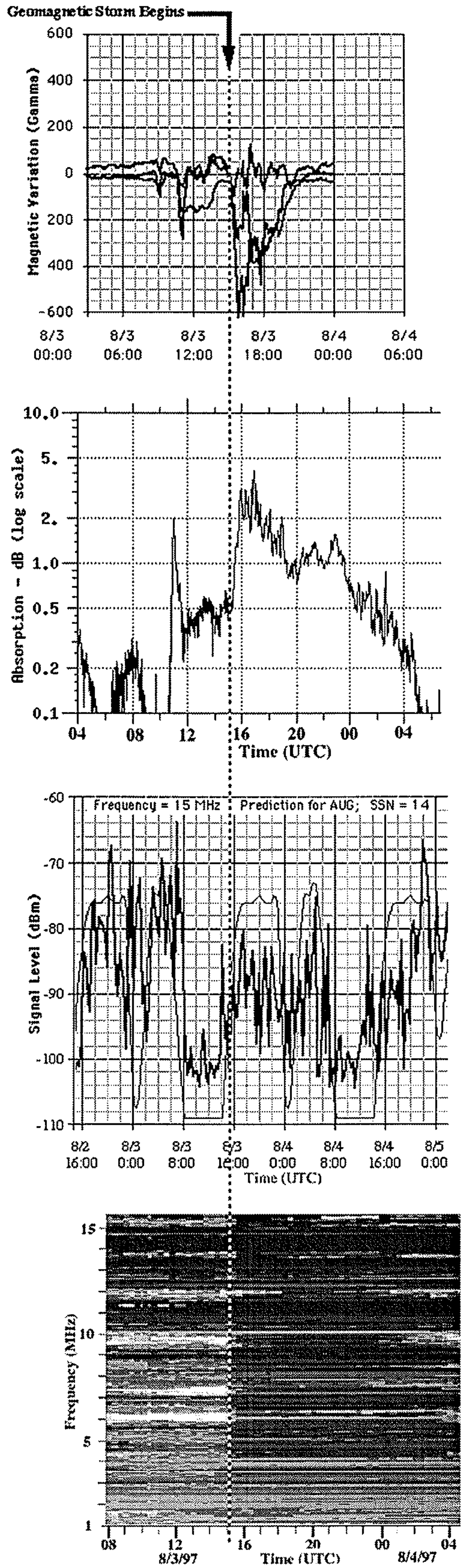


The magnetometer showed increased Magnetospheric activity beginning around 1100 UTC with a small, short duration increase. This was followed by a return to nearly quiet conditions but a large and dramatic increase in geomagnetic activity began again just after 1500 UTC and continued for several hours.

The 30-MHz riometer showed a large increase in overhead absorption, starting just after 1500 UTC, corresponding exactly with the large change observed in the magnetometer readings. Riometer absorption above 1 dB generally indicates poorer communications in the HF bands.

Signal levels observed at the HAARP site from the standard time and frequency stations WWV/WWVH near 15 MHz showed reduced strengths after 1500 UTC, in accordance with the magnetometer and riometer observations.

The spectrum monitor, which records signal strengths over a wide band of frequencies, showed abrupt loss of signals (communications blackout) throughout the entire HF band starting at 1500 UTC and lasting until early into the next day.



Effects of a coronal mass ejection from the sun on August 3, 1997, as observed on a number of HAARP diagnostic instruments at Gakona, Alaska.

Examples of HAARP research areas

Lithosphere and the Earth's crust
- Make soundings of the ocean floor, deep oil reserves, and the coastal marine environment

Mesosphere (60–120 km altitude)
- Develop techniques for long-term monitoring of the "ignorosphere"
- Study global warming and ozone depletion issues via observations of changes in mesospheric chemistry, composition, temperature distribution, and dynamics

Ionosphere (50–1,000 km altitude)
- Investigate ionosphere physics and chemistry
- Quantify efficiencies of processes initiated by radio waves
- Study ionospheric–magnetospheric coupling processes

Magnetosphere (1,000–10,000 km altitude)
- Study magnetospheric density fluctuations and irregularities
- Identify auroral acceleration mechanisms
- Develop and validate models of the auroral magnetosphere

the transmitter, although confined to the 2.8- to 10-MHz frequency range, can be converted down in frequency to coherent low-frequency waves spanning five decades from fractions of a hertz to tens of kilohertz. It can be converted up as well, producing emissions in the infrared (IR) and visible spectra. Furthermore, it can structure the ionospheric electron densities in a way that provides a controlled scatterer of radio signals for HF/VHF/UHF frequencies. As a result the transmitter can generate sources for remote sensing and new radio wave system applications spanning 16 decades in frequency. A detailed description of these remote sensing and applications-related research areas, along with recent research results related to them, will be the subject of a future article.

Land Tenure and Economic Collapse in Northern Siberia

This report was prepared by John P. Ziker, Department of Anthropology, University of California, Santa Barbara.

This research was supported in part by a grant from the National Science Foundation's Arctic Social Science Program. In addition, the 1997 research was supported by a grant from the International Research and Exchanges Board (IREX), with funds provided by the National Endowment for the Humanities and the U.S. Department of State, Program for Scientific Research in Russia, Eurasia, and Eastern Europe. The research conducted in 1996 was supported in part by a grant from the American Council of Teachers of Russian (ACTR), with funds provided by the U.S. Department of State, Program for Research and Training on Eastern Europe and the Independent States of the Former Soviet Union. Field research conducted in 1995 and 1996 was also supported in part by a Humanities/Social Science Research Grant from the Graduate Division, University of California, Santa Barbara.

The lives of indigenous peoples in the Siberian Arctic have changed dramatically since the dissolution of state socialism and subsequent economic transformation. Since a 1992 Russian presidential decree, Siberian Natives, referred to in Russia as "small-numbering peoples," have been allowed to claim "family and clan" holdings on lands previously allocated to rural state enterprises. Through these holdings the 1992 decree intended to protect traditional economic activities and territory. Despite the opportunities offered by regional regulations for the issuance of family/clan holdings, the majority of Native households living in 17 remote settlements have not taken claim to the land. Since 1992 only 50 family/clan holdings have been formed in the region where this research was focused—the Taimyr Autonomous Region of northern Krasnoyarksii Krai.

From late 1995 through 1997, I lived a total of 12 months in the community of Ust Avam in the central Taimyr lowlands. Two Native groups, the Dolgan and the Nganasan, and a minority of non-indigenous people from all over the former Soviet Union populate the Avam tundra and settlement of Ust Avam. During my time in Ust Avam, I studied historical and current land tenure patterns, employment, mixed hunting/fishing/trapping economies, and exchange with the larger economy in order to track the strategies employed in this time of rapid change.

Ethnographers in the former Soviet Union have recently observed an expansion of self-interested strategies among a variety of groups and have associated negative social effects with these behaviors. For example, Kathleen Kuehnast observed that the introduction of the market economy in Kyrgyzstan has led to black marketing and speculation, while privatization of enterprises led to a host of other social problems, such as prostitution, drug trading, begging, and homelessness. Nora Dudwick confirmed that the dissolution of socialism led to atomization of social and economic life in a variety of rural locations, bringing on mutually reinforcing poverty and isolation.

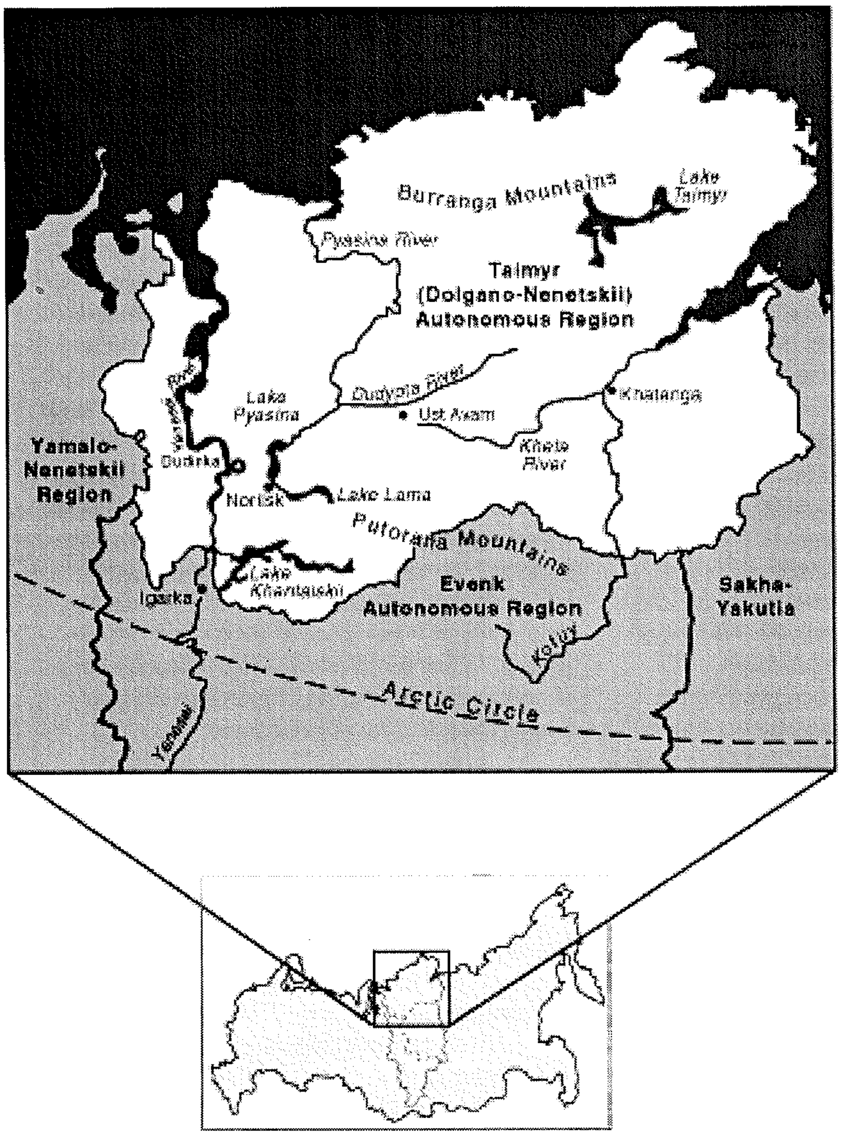
Despite the negative effects of rapid financial and infrastructure changes, as well as the lack of involvement in land claims, a large number of Native Siberians are maintaining social and economic traditions. While the transition period is creating hardship, in some respects this hardship keeps the community together. For example, land use in the Avam tundra has gone from intensive production stimulated by government enterprise salaries and bonuses to production mainly for family subsistence. With a growing local subsistence economy, Native families are employing traditional sharing networks, reciprocal land use, and their hospitable tundra code. As a result of this project, I have found that there is little apparent benefit to residents in the Ust Avam community for pursuing household land grants.

Models of social change in the Arctic and research methods

Russian ethnographers A.A. Pika and V.V. Prokhorov proposed that the transition to capitalism should supplement traditional aspects of the northern Native mixed economy with modern implements and information. The result should be a revitalization of northern indigenous ethnicity. Are contemporary family/clan holdings an example of this neotraditionalism? And what are the implications for the vast majority of households not taking territory as a family/clan holding?

Pertti Pelto proposed another model of north Eurasian development. In Pelto's model, mechanized transport replaces animal- and human-driven transport. As a result, people become dependent on nonlocal energy sources, industry, and politics, and this leads to socioeconomic differentiation of aboriginal families. This process already occurred among Native Siberians under socialism. Are family/clan farms, then, a further example of entrepreneurial activity and socioeconomic differentiation under capitalism?

I have amended Pelto's model to provide an alternative to both his and the neotraditionalist model. The key concept in my model is the decrease in dependencies on the larger economy. In Ust Avam, people are less dependent due to changes in access to government and services.



Taimyr Autonomous Region of Krasnoyarskii Krai.

Reliance on the local subsistence economy and sharing networks are the result, with reduced exchanges in the larger economy.

Despite the rather liberal conditions under which family/clan holdings can be obtained, very few families have actually taken the new (that is to say, "traditional") form of land holding in the heart of the tundra. Out of the Native population of the Avam tundra area, over 600 individuals, only four families have taken claim to traditional territories (and three of these are hundreds of kilometers from Ust Avam in the direction of urban centers). Most of the other 50 or so family/clan holdings in the region are close to the regional capital, Dudinka, or the industrial city of Norilsk. Why did so few decide to take legal control of ancestral lands? To understand the motivations for their not taking family/clan holdings, I surveyed Native families still retaining rights to state enterprise holdings, as well as several that had claimed a family/clan holding.

This project compared households that maintain use rights to state enterprise land with those that have taken the family/clan holding. The research employed ethnographic and sociodemographic methods along with archival research. The focus area was the Avam tundra population located in the Taimyr Autonomous Region of Krasnoyarskii Krai, Russia. I also worked for several months with three other rural Taimyr communities and in Dudinka.

To evaluate alternative explanations of social and economic change in the Ust Avam, I documented changes in the importance of the subsistence and cash sectors, changes in land use and the local economy, and relationships with the macroeconomy. Interviews focused on the reasons for establishing family and clan farms or for remaining in the state enterprise. Participants were asked their opinions on changes in the relative importance of generalized sharing, delayed returns (and other forms of aid), balanced exchange, barter, and antagonistic exchange prior to and after the breakup of the Soviet Union. Participants were interviewed about income, expenses, sources of capital equipment, and spare parts prior to and after the break-up of the Soviet Union. I report some results from the first two points below.

In addition to the structured surveys, the research employed participant observation and informal, unstructured interviews to get an idea of the history of the population and its resource use patterns. Archival and statistical data made available by various offices of the Taimyr regional government were also used. My theoretical goal was to find out if these individuals, participating in a mixed hunting, fishing, and trapping economy under rapid transformation, were pursuing self-interest, minimizing risk, optimizing some other utility, or following mixed strategies with group-determined aspiration levels. A similar range of strategies is also found in theoretical study of hunter-gatherer exchange and traditional economies.

The Ust Avam settlement administration cooperated with me on my project and facilitated my census of the area. There were 673 individuals (167 households) registered to live in Ust Avam and the surrounding tundra. The administration of Ust Avam defined households as those individuals living together in one apartment. I interviewed 79 individuals, a random sample of adults working in the four main income sectors in Ust Avam and surrounding tundra. The income sectors are:

- The "Taimyrskii" government hunting enterprise;
- Budgetary organizations, including the settlement administration, school, health clinic, and post office;
- Federal pensions and unemployment; and
- The store and bakery.

The exchange data presented below are based on these interviews.

The local situation

The economic situation in Ust Avam is bleak. Native workers are being laid off from the government hunting enterprise, and no new jobs are being created. Still, most households participate in the local hunting, fishing, and trapping economy. Producing households share meat and fish with relatives, friends, single mothers, pensioners, and other people who ask; no one is starving. In the words of one hunter, "Bihigi eredebenebit" ("We are surviving").

Decades of capital-intensive development by the Soviets incorporated Native reindeer herders and hunter/fishers into the larger political economy. For workers in rural industry, the standard of living was relatively high. State-owned enterprises, regional government, and trade unions provided housing, jobs, education, and some vacation travel expenses. Native workers in Ust Avam returned traditional bush products, such as caribou meat, whitefish, fine furs, and crafts to the state, and they also worked in technical support positions in the diesel generating station, warehouse, and tractor service.

Since 1991, exchange with the state has diminished. The remnants of the state enterprise, as well as private traders and speculators from Norilsk—where the world's most northerly, and third largest, mining and metallurgy combine is located—do not supply fuel, groceries, and building materials in previous quantities. In Dudinka and Norilsk it is more economical for consumers to purchase lamb imported from New Zealand and beef from Austria than reindeer meat from their own Native villages. This collapse in domestic production is widespread across the Russian Federation.

The government hunting enterprise "Taimyrskii," created by the Soviet of Ministries in 1971, was the culmination of close to 40 years of collectivization in the Avam area. Hunting wild reindeer replaced domestic reindeer herding in the 1970s. By 1978 there were no domestic reindeer left, and most of the community's households had moved to the Ust Avam settlement. Prior to the collapse of the U.S.S.R., Taimyrskii employed Dolgan and Nganasan men to hunt caribou, fish, and trap in the organization's 10,000,000-hectare land grant. Brigades of hunters, sometimes comprising nuclear families or adult siblings, worked on assigned hunting territories of up to 2000 square kilometers. Until 1992 each brigade had a plan for a certain quantity of meat, fish, or fur each year. With fulfillment of the plan, brigade members received payments, and each brigade received supplies and capital improvements, such as snowmobiles, hunting cabins, nets, and steel leg-hold traps. Women generally worked for the Taimyrskii's craft workshop, sowing beaded sections for caribou fur boots, called untaiki. The enterprise constructed the houses, school, clinic, diesel generating station, and warehouses. It continues to manage supplies of fuel, supplies, and foodstuffs, but not at pre-1992 levels.

Since 1992 Taimyrskii has eliminated brigade plans, stopped capital investments, and often delayed salaries for months. During the winter of 1997, two months' salaries were frozen, and the enterprise made no promises to pay their workers for bush products turned in at that time. Although many had not received salaries for years, Taimyrskii still employed, on paper, half of Ust Avam's working population (146 adults) in 1997.

The family/clan holdings in the Ust Avam area were formed several years ago (1993–1995). They received low-interest government loans to aid in purchasing capital equipment and supplies. Currently two out of four of these holdings are inactive (that is, not used regularly) because of difficulties associated with transportation.

Family/clan holdings in the Avam tundra

Below, I report and analyze the results of my survey questions: "Why did you claim a family/clan holding?" And for those without family/clan holdings, "Why did you not claim a family/clan holding?" I asked these questions to 25 individuals who are professional hunters in the Avam tundra. I interviewed at least one hunter from each of the 17 active hunting brigades in Taimyrskii, as well as the heads of three family/clan holdings and two individuals who work at surrounding state enterprises. In all but three cases, these individuals are the leaders of the hunting brigades or holdings. These professional hunters represent approximately half of the professional hunters in Taimyrskii, and according to my observations, are generally the most active Native hunters in the area. Twenty-two of 25 respondents were not associated with family/clan holdings.

Five of the 22 responses to the question "Why did you not claim a family/clan holding?" dealt with the concept of the family/clan holding. Three of these individuals said that they did not understand what a family/clan holding was or how it could actually work. These responses point to the lack of information and crumbling infrastructure in the region. The other two individuals said that they doubted that it was possible for them to take a family/clan holding. This response underscores the difficulties associated with getting the necessary approvals, completing the paperwork, and dealing with government officials.

Two individuals without family/clan holdings expressed intent in claiming a family/clan holding. One of these individuals expressed his interest in claiming ancestral lands to protect them from Russian expansion. After making several statements on the relative position of the Taimyr Natives in regional society, that informant expressed his doubts about the reality of claiming the land. The other individual stated that he initiated the paperwork for making a land claim but was not clear about its status. He stated that he had not yet been approved because something was missing. Again, both of these responses point to the difficulties associated with getting the necessary approvals, completing the paperwork, and dealing with government officials in the distant capital.

One respondent is officially listed as a member of a family/clan holding, but he did not quit his job with the government hunting enterprise, and the family/clan holding has never been active. In fact, the head of that holding has not visited the land since his claim was approved in 1994. This hunter's opinion on my question was: "We took the land because our hunting spot was there. We don't know anything; there is no result." Again, this response points to the lack of information and crumbling infrastructure. There is no longer a middleman for the hunter/fisher/trapper actually producing. It is close to impossible for the hunter to deal directly with organizations that sell goods in urban markets. The historical middleman, the government enterprise or state farm, is incapacitated.

Money was the main factor in not starting a family/clan holding for 10 respondents. There were three kinds of problems these informants associated with money. Four informants mentioned the lack of starting capital as the main reason for not claiming land. Five informants stated that family/clan farms were not claimed because "it's not profitable." Their concerns are probably justified since two of four family/clan farms in the area are inactive, a situation that is similar in other parts of the region. The third problem associated with money had to do with obtaining supplies, such as gas, coal, and consumables, along with distribution and marketing. Five informants mentioned these infrastructural problems as a first or second reason for not starting a family/clan holding.

One informant stated that he had no reason to make a family/clan land claim. He clarified that the land is poor (that is, resources are migratory). In addition, he mentioned the problems with obtaining supplies and marketing his production.

Another individual stated that he had no right to lands there since he was not local. He clarified that he "never thought about it." He is married to a local woman, however, and there are prior instances of family/clan holdings being granted to Native and non-Native men married to a woman in a Taimyr Native community.

Overwhelming paperwork was mentioned by one individual as the main reason for his not making a land claim. It is true that it takes several weeks, if not months, to complete the paperwork and get the approvals necessary for starting a family/clan farm in the Taimyr region. This process must be conducted in Dudinka, which is difficult for hunters who spend months on end in the tundra.

One individual stated that he did not know why he did not decide to start a family/clan holding. This individual spends most of his time in the bush and has rarely visited the regional capital or Norilsk. It is not surprising that claiming a family/clan holding was not in his interests.

Three individuals with family/clan holdings were asked the question "Why did you claim a family/clan holding?" One individual stated that he hoped to live better. This individual alone admitted entrepreneurial motivations in claiming a family/clan holding. The reality is that taxes consume all his profits, however, and his holding is barely active.

Another individual stated that the main reason for starting a family/clan holding was to feel more liberty. Being one's own boss is a reason why many individuals in the U.S. start businesses too.

This family/clan holding was the only active one in the Avam tundra.

The third individual with a family/clan holding stated that he did not know why he started a family/clan holding. Upon cross checks with other informants in his community (150 km from Ust Avam) I discovered that he received capital equipment from the government hunting enterprise when he made his land claim. The equipment he received is already lost or broken. Currently he works for the government hunting enterprise by contract during certain seasons, and his family/clan holding is inactive.

In sum, there is insufficient time and money and little apparent benefit for residents in the Ust Avam community in pursuing official land grants under current regulations and economic conditions in the Taimyr region. Most hunters are busy hunting. They do not have the time or the political capital necessary to push their land claims through the system or to market their production. In addition, there is little competition for hunting grounds, still officially held by Taimyrskii. Those individuals with family/clan holdings have made little, if any, material gains. Although material gain was not the goal of the 1992 presidential decree, it appears to have been the goal for at least some of those individuals creating family/clan holdings in the Taimyr region.

Local exchange after 1991

A total of 79 representatives of households participated in a more general survey questionnaire I conducted in the Avam community. These representatives included a random sample of Native men and women from the four income sectors defined above as well as the three heads of family/clan holdings. The survey questions focused on changes in five modes of exchange prior to and after the breakup of the Soviet Union: generalized sharing, delayed exchange, balanced exchange, barter, and antagonistic exchange.

The first question had to do with the sharing economy. Historically among the Dolgan and Nganasan, meat and fish was shared among households in a camp. This practice is similar to sharing in other groups of hunter-gatherers. In my questionnaire I asked: "When a hunter returns to the settlement with catch from the tundra, this catch is often shared. Is this sharing less, the same, or more than prior to 1991?" Forty respondents (50%) stated that sharing had decreased since 1991. On follow-up inquiry, 16 respondents stated that hunting households now were acting more for their own and close relatives' benefit. Twelve stated that hunting households wanted money or alcohol in exchange more often than before. Seven respondents cited fewer caribou in the area, due to changes in caribou migration patterns, as the main cause. Twenty-five respondents (32%) stated that the sharing of bush products was the same. "Tradition" was the most frequent answer to my follow-up question of why generalized reciprocity was the same. Surprisingly 12 respondents (15%) stated that generalized sharing had increased. These individuals cited a greater need in the village and fewer people producing food since 1991. The three heads of family/clan holdings each answered differently. One indicated more sharing, one said that it was the same, and the other stated that sharing had decreased.

The second question had to do with delayed exchange, or mutual-return aid (vzaimno-obratnaya pomoshch). In the Russian Arctic, mutual aid has long been documented among Native peoples. The state demonized mutual aid, as a sign of primitive communism, during collectivization. Nevertheless, mutual aid remained to mitigate the dangers and rigors of travel and the irregularity of spare-part supply. During interviews I asked, "When you need something, for example, a spare part or groceries, you can ask someone, for example, a relative, a friend or an acquaintance. In the future you promise to help them out with something. Does this kind of mutual-return aid occur more, the same, or less than it did before 1991?"

Thirty-nine of 79 heads of households (50%) stated that delayed reciprocity had decreased since 1991. Upon follow-up, ten of these individuals stated that people had changed and become greedier. Nine informants stated that things, such as spare parts, had become rare and expensive. Five believed that they had nothing with which to help others.

Thirty-four of 79 heads of households (43%) stated that delayed reciprocity was the same as it was before 1991. Having close social relationships (proximity and kinship) and tradition were the most frequently mentioned reasons for the continuation of delayed reciprocity. Five individuals stated that delayed reciprocity was more important now than before 1991. Again, the results from the family/clan holding heads were mixed. One stated that delayed exchange was practiced more than before 1991, and two said that it was practiced less often.

Barter was widely practiced in the Taimyr region prior to the establishment of Soviet rule in

1930. Merchants traded consumer goods for pelts since Russian expansion into the region in the 1600s. Although barter was outlawed during socialism, it continued behind closed doors. I asked a similar question about changes in the barter economy: "When you need something, for example, a spare part or groceries, you can trade for something that you have, for example, meat, furs, or alcohol. Does this kind of barter occur more, the same, or less than prior to 1991?" Forty-one respondents (52%) answered that barter occurs more often than before 1991. The top three reasons why these individuals believed that barter had increased are: life has changed, there is no money now, and barter was not allowed before 1991. Twelve of the 79 household heads (15%) stated that barter occurs with the same frequency. Surprisingly 11 respondents (14%) stated that barter occurred less often. These individuals explained that their products were in higher demand before 1991 (when they still "traded well"). Fifteen respondents (19%) had no opinion or did not know about barter; I interpret their lack of opinion as implicit recognition of the illegal (during socialism) or tax evasive (after socialism) nature of barter. Two of three family/clan household heads stated that barter was practiced more often than before 1991. The other stated that it was practiced less often.

To get an idea of how the changes in the larger economy have impacted the population's purchasing power, I asked about balanced exchange through cash purchase: "You buy something with cash, for example, groceries, spare parts, holiday trips. Does this occur more, the same or less than prior to 1991?" The overwhelming majority of respondents, 64 of 79 heads of households (81%), stated that they purchase less with money now than they did before 1991. Lack of money (due to delays in paying salaries and welfare) was the most common explanation (45 respondents). Lack of things to buy in the store was the second most common explanation (11 respondents). Twelve of the 79 household heads (15%) stated that they buy more now than before 1991. The most common explanation was that things could be purchased only with money now. Before 1991, connections were more important than money in purchasing certain consumer goods. Three household heads (4%) stated that money purchasing was about the same as it was before. Again, the results from the family/clan holding heads were mixed. Two stated that purchasing power was less than prior to the breakup of socialism. One believed that his purchasing power was greater than in 1991.

Lastly, to get a picture of changes in egoistic behavior, I asked about antagonistic exchanges or negative reciprocity: "It happens that someone borrows something and does not return it. Does this occur more, the same, or less frequently than prior to 1991?" Forty-one (52%) of the 79 household heads stated that people were defecting on social exchanges more now than before the breakup of the Soviet Union. The informants mentioned the lack of salaries and changes in people (that is, becoming less trustworthy) as the reasons for their perceived increase in defections. Eleven informants (14%) stated that negative reciprocity was the same as it was before 1991. Another eleven (14%) stated that negative reciprocity had actually decreased since 1991; most of them explained that they have nothing left to take. Sixteen informants (20%) did not know or had no opinion. This question was intended to get at defections on social exchanges (borrowing items). My impression from answers to the follow-up question of why they believed negative reciprocity had changed was that people in Ust Avam are being more careful in lending their things. Two of three family/clan holdings heads did not know or had no opinion. The other stated that defections on social exchanges had increased.

In sum, approximately half of the heads of households interviewed stated that the level of giving meat and fish was the same or greater than it had been prior to the breakup of the Soviet Union. The other half stated that this practice had abated. Similarly half of the respondents stated that delayed exchange had abated, while the other half stated that it had remained the same or increased. These differences might be related to age differences in the heads of households interviewed. Many elderly informants stated that generalized and delayed exchange had decreased since the breakup of the Soviet Union. Younger producers typically answered that they give more.

Most respondents stated that their abilities to make cash purchases have decreased since 1991. This result is expected, considering the severe budgetary problems within the Russian Agricultural Ministry. Many informants were of the opinion that barter exchanges have increased since 1991, partially as a result of the lack of money for cash purchases. A few informants noted that barter equivalencies have become more disadvantageous for Native producers in recent years, and thus they practice barter less often. Similarly the majority of informants stated that self-centered,

Nina Logvina, her son Igor, and his son. They are Nganasan of the shamanic Kosterkin lineage and live in Ust Avam.

antagonistic exchange, or defections on exchange, have increased. To some extent opinions shift depending on what frame of reference I gave. If informants were referring to friends and family, informants stressed their sharing traditions. If informants were referring to visitors and administrators, informants tended to emphasize the negative aspects of recent change.

Conclusion

Ethnographers have recently observed expansion of self-interested strategies and hostile social behaviors among a variety of groups in the former Soviet Union. In many regions the dissolution of socialism and the introduction of a market economy led to black marketing, speculation, prostitution, drug trading, begging, homelessness, and mutually reinforcing poverty and isolation. In the north Siberian community of Ust Avam, Russia's rapid and unpredictable economic transition has created hardship. The vast majority of household heads I interviewed indicated they were in a worse socioeconomic position than in 1991. Despite the hardship, Ust Avam's families are sustaining themselves. With a local subsistence economy growing in importance, Native families are employing traditional sharing networks and reciprocal land use.

The importance of the land and its resources has changed in the 1990s. In the 1970s and 1980s government policy and finances stimulated intensive production and resulted in the division of the land into brigade hunting territories. Many of these brigades comprised nuclear family members, but some included distantly related or nonrelated individuals in abutting living spaces. Today there is little apparent benefit to residents in the Ust Avam community for pursuing household land grants. Obtaining a family/clan holding is time consuming and expensive. A hunter would have to travel to the capital more than once during the process. In addition the lack of involvement in land claims may, in part, be due to family subsistence requirements and the migratory nature of renewable resources.

Those owners of family/clan holdings located near the regional capital and the Norilsk industrial district have more direct contact with the administrative apparatus and are more easily involved with the formal economy through barter and direct sales of meat, fish, and fur. Two of the family/clan holdings in the Ust Avam tundra have been largely inactive since their inception. The other two are close to Norilsk, and one is regularly involved in sales and barter. The remaining Native households in the rural communities investigated (the vast majority of the people) maintain mixed economic strategies focused on subsistence. Hunters and fishermen produce goods for their household, extended family, relatives, and other people in the community. In the countryside, kinship networks are important in distributing the majority of locally produced meat and fish along with some purchased consumer goods. These networks are significant since goods and services are provided at no charge. Kinship and friendship facilitate the ability of some hunters to use other hunters' territories. A small amount of locally produced goods—a much smaller quantity than during Communism—continues to be supplied to state rural enterprises in exchange for supplies and unpredictable cash payments.

An increase in ethnic violence, predicted by some scholars for this region, is not occurring with the growth of family/clan territorial holdings. Rather, traditional ethnic distinctions are losing importance after forced settlement in the 1960s and subsequent intermarriage between ethnic groups. New identities are developing based on communities of residence. In Ust Avam I observed meat and fish sharing networks that regularly cross Native ethnic boundaries.

This research contributes to the fields of anthropology, Arctic social sciences, and Russian studies. Currently there is a dearth of ethnographic materials in English for indigenous Siberian populations, especially the Dolgan and Nganasan. This research provides the basic ethnography for a little studied region of Siberia.

Rapid social change, community viability, and land tenure are problems faced across the circumpolar north. The particular expression of these issues in northern Siberia is an interdisciplinary problem, and this research adds to the available literature. Finally a study of northern Siberia is not complete without analysis of the interactions of the Russian government and non-Native population in the region. The research provides detailed information on the Taimyr Region's history and government relationship with Native groups.

While supporting the United Nations decade of aboriginal peoples and after years of integration with the planned economy, Russia's current policy toward its own indigenous groups is ambiguous. The presidential decree was never passed as a law, and the government's current policy, as seen from Native rural communities in the Taimyr Region, is one of "live as you like." The information presented in future publications should be useful for indigenous Siberians and the Russian government by documenting the problems faced on the ground. By providing a case study, this research should also be useful for the international community, in particular those interested in human rights, aboriginal peoples, and sustainable development.

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Collaborative U.S. and Russian Studies of Rheumatic Disorders

Spondyloarthropathy in Circumpolar Populations

This article was prepared by Reva Lawrence, National Institute of Arthritis and Musculoskeletal and Skin Diseases; Georgiana Boyer, Alaska Area Native Health Service, Anchorage, Alaska; Lydia Benevolenskaya, Institute of Rheumatology, Russian Academy of Medical Sciences, Moscow; David Templin, Alaska Area Native Health Service, Anchorage, Alaska; Shandor Erdesz, Institute of Rheumatology, Russian Academy of Medical Sciences, Moscow; Stephen Heyse, National Institutes of Health, National Institute of Allergy and Infectious Diseases; and Donald Everett, National Eye Institute.

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Studies of spondyloarthropathy (Spa) grew out of shared U.S. and Russian interest in a poorly understood and inadequately described group of rheumatic diseases that appeared to be responsible for an appreciable burden in circumpolar populations.

The term spondyloarthropathy defines a group of related inflammatory joint diseases that share characteristic clinical features. These features include arthritis in the spine or in the peripheral joints, sacroiliitis, tendinitis, and in some instances inflammation of the eyes, the intestine, the heart, and other organs. The cause or causes of the Spa are not well understood, although it is clear that both genetic and environmental factors play a role. Among the disease subgroups of Spa are ankylosing spondylitis, reactive arthritis, psoriatic arthritis, arthritis associated with chronic inflammatory bowel disease, and undifferentiated Spa. All of the spondyloarthopathic diseases appear to be associated to some degree with the major histocompatibility complex class I molecule HLA-B27. Some are clearly triggered by infection with Chlamydia or with gram-negative organisms such as Salmonella or Shigella. Joint U.S. and Russian studies of Spa in indigenous circumpolar populations were stimulated by the knowledge that the study populations were known to have a much higher frequency of HLA-B27 than in other populations, and a high prevalence of Spa was previously reported in other Native groups of Greenland, Canada, and Alaska.

Several informal discussions were held by representatives of the National Institutes of Health (NIH) and the Alaska Native Health Service of the U.S. and the Institute of Rheumatology of the U.S.S.R. These meetings preceded the decision to plan and conduct collaborative epidemiological studies of spondyloarthropathy in Alaskan and Siberian Eskimos plus Chukchi people who share the peninsula with the Siberian Eskimos. It was agreed that these indigenous populations of Siberia and Alaska were uniquely suited for epidemiological studies because they share common ancestors and may be expected to share many genes, quite possibly including those that confer susceptibility to spondyloarthropathy. In addition, the indigenous populations are geographically defined, relatively stable, and homogeneous, and they generally have large family constellations living nearby, all desirable characteristics for epidemiological and family studies.

Five planning meetings were held to discuss study objectives, research design, disease criteria, methods of data collection and analysis, and details of the core data collection instrument. The shared components consisted of a personal interview, a physical examination, a laboratory examination, and in certain cases, pelvic radiographs. Pilot data were collected and reviewed prior to full study implementation. Because of the different sizes of the U.S. and Russian study populations and the circumstances of health care delivery in the two countries, certain study objectives were better suited in one setting than the other. Thus the collaborators designed their studies to be complementary rather than identical.

Both U.S. and Russian investigators carried out cross-sectional surveys to assess disease prevalence. In addition to cross-sectional data, U.S. investigators collected longitudinal data over a five-year period to examine clinical manifestations, natural history, disease impact, and health care utilization. The overall aims of these studies were to describe the spectrum of spondyloarthropathy in these populations and to lay the groundwork for investigations of the role of specific genetic and environmental factors in the pathogenesis and expression of the disease.

Methods

During three expeditions to Siberia, Russian investigators from the Institute of Rheumatology collected data from four settlements (Sireniki, Novo-Chaplino, Erunelen, and Nunligran) on the Chukotka peninsula for a cross-sectional study of disease prevalence. Institute investigators introduced the project to local medical personnel, explained the aims and goals of the project, and requested assistance in the study to maximize local participation and to address ethical issues.

The project received support and approval from the Russian Academy of Medical Sciences and was approved by the Administrations of the Chukotka District and the Magadan Region and Chukotka District Hospital. The study was carried out with the cooperation of the local health offices. To encourage full participation in the project, local health personnel contacted residents. Informed consent was obtained prior to examination, and residents were informed that medical findings would be added to participants' local medical records. Eighty-three percent of the eligible residents participated in the study.

U.S. researchers collected cross-sectional data from Eskimos in four Alaskan regions for studies of prevalence and five years of longitudinal data for studies of clinical manifestations, natural history, disease impact, and health care utilization. The study settings in Alaska included the North Slope Borough and Kotzebue health service regions, traditional territories of Inupiat Eskimo, and the Bristol Bay and Yukon–Kuskokwim Delta regions, inhabited primarily by Yupik Eskimo. The Inupiaq are closely related to the Inuit of Canada and Greenland. The Yupik are linguistically related more closely to the Siberian Eskimo of Russia than to the Inupiat.

The U.S. investigators used multiple means to collect data for their cross-sectional and longitudinal studies of Spa. These investigators were employed by the Indian Health Service (IHS). The U.S. team of physicians had extensive experience collecting data in this population and providing health care. One had previously served as an IHS rheumatologist in Alaska. Investigators began their data collection by identifying all Native residents of the two study regions with a diagnosis of any inflammatory arthritis or problems characteristic of Spa through queries to existing rheumatic disease registries, health care providers, and the Alaska Area Health Service (AANHC) computerized patient information system. Records of all possible cases accumulated from these various sources were reviewed. Those persons considered to have possible Spa following preliminary review of their medical records were invited to attend clinic for further evaluation. All study participants received descriptions of the study and gave informed consent.

The research protocol for the study was cleared at several levels before any data collection was begun. Approval was obtained in writing from Service Unit Health Boards (elsewhere in the U.S. these would be called Tribal Health Boards). The directors of local health facilities also supplied written agreement. The protocol was also reviewed and approved by the AANHS Research and Publications Committee, which functions as an Institutional Review Board (IRB) for evaluating the moral, ethical, and scientific appropriateness and questions of cultural sensitivity. Finally the proposal was reviewed and approved by the National Indian Health Service Research and Publications Committee and IRB. This extensive clearance process was carried out to protect the American Indian/Alaska Native populations from unethical, needlessly intrusive, physically dangerous, or unnecessary studies. Upon implementation of the protocol, participants received descriptions of the study and signed informed consent. Periodic reports on the progress, funding, and impact of the studies were made to local health boards and communities. All examined participants who were in need of treatment by a rheumatologist were placed on treatment and/or referred to local arthritis clinics. All diagnostic information collected in the study was entered into the patient care information system. Support for the project was provided by the National Institutes of Health, National Institute of Arthritis and Musculoskeletal and Skin Diseases, through an interagency agreement with the Indian Health Service, Alaska Area Native Health Service.

Results and conclusions

In the parallel prevalence studies of Alaskan and Chukotka indigenous populations, a similar overall prevalence of Spa and spectrum of disease were found in the geographically separated but genetically related populations, although very different ascertainment methods were used. Combined, the prevalence of all types of Spa was 4.5% among adults positive for the presence of HLA-B27 in these populations with a high prevalence of HLA-B27. Overall, the prevalence of Spa and spectrum of disease were found to be very similar, including reactive arthritis, ankylosing spondylitis, and undifferentiated Spa. Psoriatic arthritis was very rare. No predisposition to one particular form of Spa was observed in the various cohorts.

One useful finding from the U.S. study was that Spa was substantially under-diagnosed in the community, particularly in women. For many years most Spa disease was considered primarily a male disease. When investigators were able to examine the ratio of male to female cases through the use of active surveillance methods, rather than relying on passive reporting in clinical settings, a community-

Number of cases of different Spa syndromes by ethnicity

	Population screened	Reactive Arthritis*	Ankylosing Spondylitis	Undifferentiated Spa	Psoriatic Arthritis
Chukchi	525	3	4	2	0
Siberian Eskimo	424	3	5	2	1
Inupiat Eskimo	2173	22	6	21	0
Yupik Eskimo	2698	18	9	27	1

* Includes Reiter's syndrome

based picture of the disease emerged that was much more equal between the genders. However, men were more likely to have severe disease. U.S. investigators also examined the possible reasons for under-diagnosis. A review of undiagnosed Spa patients' records made it clear that many with symptoms had sought medical care for back and joint complaints but that the health care providers were reluctant to diagnose or did not recognize the disorders as part of the Spa spectrum. Investigators noted with concern that so many cases of Spa are missed in the primary care setting. Analyses of the U.S. longitudinal data are in progress to examine clinical manifestations, natural history, disease impact, and health care utilization.

This program provides an example of the feasibility of conducting international collaborative studies in indigenous populations with a minimum disruption to the Native people and with a benefit to individuals, communities, and the health care system. This project stimulated opportunities for additional training and collaboration by Russian scientists. Finally, two epidemiological workshops were held, one in the U.S., the other in Russia, that included the participation of many additional international investigators. U.S. and Russian study colleagues hope that their experience will stimulate further collaboration between member nations of the circumpolar community.

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Back Cover

Boris Elogir, a Dolgan and highly decorated professional hunter in Ust Avam in the Siberian Arctic, resting after returning to the cabin with the day's catch. See page 73 for a discussion of how recent economic changes have affected indigenous peoples in Siberia.

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