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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 (IARPC) and the Arctic Research Commission (ARC). Both the Interagency Committee and the Commission were authorized under the Arctic Research and Policy Act (ARPA) 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.

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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Front Cover

This colorful image shows a portion of the North Slope of Alaska and adjacent Beaufort Sea. It was acquired on August 16, 2000, using the Multi-angle Imaging SpectroRadiometer's nadir (vertical-viewing) camera aboard the Terra satellite. The swirling patterns apparent on the Beaufort Sea are small ice floes driven by turbulent water patterns, or eddies, caused by the interactions of water masses of differing salinity and temperature. By this time of year, all of the seasonal ice that surrounds the north coast of Alaska in winter has broken up, although the perennial pack ice remains farther north. The morphology of the perennial ice pack's edge varies in response to the prevailing wind. If the wind is blowing strongly toward the perennial pack (that is, to the north), the ice edge will be more compact. In this image the ice edge is diffuse, and the patterns reflected by the ice floes indicate fairly calm weather.

The Canning River flows north about halfway between the center and left side of the image, and the U.S.–Canadian border is near the right edge of the image. The two permanent human settlements within the image area are Kaktovic (near the tip of the large rounded peninsula) and Arctic Village (south of the Brooks Range, which crosses from the lower left corner to the middle of the right side). The area represented by the image is approximately 380 × 540 kilometers. The image was produced by the MISR team from NASA's Jet Propulsion Laboratory.

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SPECIAL ISSUE ON THE NATIONAL SCIENCE FOUNDATION'S ARCTIC SYSTEM SCIENCE PROGRAM

An Overview of the Arctic System Science Program

This article was prepared by Neil Swanberg, Director, Arctic System Science Program, Office of Polar Programs, National Science Foundation, and Jonathan T. Overpeck, Director, Institute for the Study of Planet Earth, Department of Geosciences, University of Arizona, and Chairman of the ARCSS Committee.

The Arctic System Science (ARCSS) program's goal is to understand the physical, geological, chemical, biological, and sociocultural processes of the Arctic system that interact with the total Earth system and thus contribute to, or are influenced by, global change. This understanding is being developed to advance the scientific basis for predicting environmental change on a seasonal-to-centuries time scale and for formulating policy options in response to the anticipated impacts of global change on humans and societal support systems.

Human societies generally observe and learn from the world around them and then use the information they gather to plan for the future. What happens to this ability if things change in unpredictable ways? Societies thrive if the changes are beneficial—for example, an improvement in climate for growing or supporting increased populations of fish or animals. However, when changes are negative, such as the disappearance of key resources or environmental features, then the consequences can often be profound. The degree to which a society is able to adapt or move may determine whether it perishes or flourishes.

We are now seeing changes in the Arctic that extend well beyond our recent human experience. The peoples of the Arctic tell us that their world is now unlike any they have known for thousands of years, according to their traditional knowledge. A good analogy for those of us who live in lower latitudes might be that spring just never came: the almanac of our traditional knowledge would become useless, and one would not know when to plant seed nor whether there would be food for newborn calves. As harsh as it seems to us, many of the peoples of the north depend on the features associated with the predictability of winter, and the platform provided by its ice, to help sustain them and the animals on which they depend. Now there is less sea ice, it is thinner and has shifted its location, the permafrost that supports the foundations of buildings and stabilizes the shoreline is melting, the timing of fall freeze-up and spring thaw has shifted by weeks in some places, and the amount of snow cover has changed, or snow has even turned to rain.

Some of these changes have obvious direct impacts on the residents of the Arctic; others act more indirectly through mechanisms such as changes in vegetation, shifts in populations of fish, migrations of land animals, or the patterns and timing of the whale migrations. All of these outcomes affect the residents of the Arctic, but there are also other, less obvious Arctic changes that may have effects that extend far beyond the Arctic. The amount of ice residing in the Arctic basin has changed, along with the surface salinities and the front between the Pacific and Atlantic water in the Arctic Ocean, and there has been a general freshening of the waters in the surface of the Beaufort Sea, all changes that could affect the deep water formation in the North Atlantic, with possible influence on global heat flux and climate.

The global change science community believes that more global change is coming, but the Arctic research community has documented change that is among the most dramatic yet observed. We need to determine whether these changes are due to natural variability or are part of some long-term trend, whether induced by human activities or not. While most of the scientific community agree that carbon dioxide and other anthropogenic greenhouse gases are the likely culprits driving this change, there is also an underlying understanding that at some level the source of the problem is secondary—we are confronted by a problem that is real, and we have an acute need to understand the system in which we live so that we can identify the scope of what to expect next. This is all made more difficult because a complex of factors affect the environment we see. The challenge is to extract understandable patterns of change.

The most troubling concern for the future may be the specter of unanticipated large-scale abrupt climate change. Although our understanding of ice-age inception is still not complete, there is little chance of a new ice age within the next several thousand years. More troubling, however, is the possibility of abrupt Arctic melting, complete with the development of a seasonally ice-free Arctic Ocean and rapidly wasting Greenland Ice Sheet. Indeed, some believe that the recent record summer sea ice retreat and thinning of Arctic sea ice could be the first signs of wholesale Arctic melting such as occurred during the last time the Arctic was warmer than present, approximately 130,000 years ago. The global impacts of such a change would be profound, including a sea level rise of up to six meters and perhaps a major shift in ocean thermohaline circulation.

The NSF ARCSS program was constructed on the premise that to understand this change we need to understand how the Arctic works as a system and how that system fits into the Earth system. This article describes how the ARCSS vision of the Arctic system has been reflected in the efforts undertaken by ARCSS, how that view has matured, and where it is leading both the program and our understanding of the Arctic system.

The Structure of ARCSS

ARCSS as a Leader

There are large international efforts underway to examine global patterns of change and the processes driving them. Programs such as the International Geosphere–Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP) have tried to reduce research on global change problems to manageable levels, more or less along disciplinary lines (hydrology, ecology, paleoclimatology, oceanography, etc.).

ARCSS set out from an early stage to view the world in a manner that reflects its physical structure. Thus, there were ocean and land components established, with the task of planning projects that focused on key domains (land, sea, air) and their interfaces with other parts of the Arctic system. To these were added paleoenvironmental and social components that sought to put the other efforts in perspective of time and to relate them to human activities. Under this structure efforts were launched to examine fluxes of heat, carbon, energy, and (newly) water through all or parts of the system. In recent years some of the global change programs have begun to migrate towards a view that resembles some of the approaches taken in ARCSS. Thus the structure IGBP is proposing for its new incarnation looks much like ARCSS has looked for years, with components related to land, sea, and air and with themes such as carbon fluxes and the water cycle to guide thinking. Moreover, there is increasing recognition in the global programs that while a global view is important, the regional view is essential to the human stakeholders and probably has considerable physical significance.

People

One of the essentials of viewing the Arctic as a system has been the recognition that humans are an inseparable part of it. This is important not only from the standpoint of how human impacts on the global system affect the Arctic, and how impacts in the Arctic affect the rest of the globe, but also because there are significant numbers of humans living in the Arctic. Moreover, people of the Arctic tend to live closer to the environment than people do in many other parts of the world. Subsistence fishing and hunting are far more common among the Native communities in the Arctic than they are in most other areas of the world. As a result, these human societies are highly susceptible to environmental changes. Where people in the rest of the world can insulate themselves to avoid environmental changes, societies that are mostly dependent on what the environment provides cannot. If seal hunts depend on seasonal ice as habitat for seals, then when the ice does not arrive they are impacted heavily. ARCSS constructed the Human Dimensions of the Arctic System (HARC) in an effort to organize research in the broad area of how humans interact with their environment and how we might help reduce vulnerability to environmental change.

The activities of this group are described beginning on page 59. The article outlines efforts to plan and coordinate social science research in ARCSS and presents brief results of some successful HARC projects. Among these are analyses linking ocean and climate changes, marine ecology, fisheries, and the development of human communities in West Greenland and other areas of the Arctic and sub-Arctic Atlantic region. Another study focuses on reindeer herding, the climate factors that influence herding practices, the role of reindeer herding in local economies, the ecological impacts of caribou grazing, and the socioeconomic consequences of losses of reindeer. Other studies included a symposium on sea ice aimed at sharing traditional knowledge and sea ice research knowledge, as well as projects on industrialization in the Kola peninsula and archaeology in Iceland.

This is an exciting area of ARCSS research that is obviously of high relevance to decision and policy making. The HARC group of scientists is attempting to link social science with natural science research. It is developing a community of social science researchers that is preparing to integrate fully with other areas of ARCSS science. The Human Dimensions of the Arctic System will continue to expand as a central part of ARCSS.

The Sea

It is a fact of geography that the Arctic is an ocean surrounded by land, so it is natural that an Arctic system science program would devote considerable effort towards ocean-centered studies. In ARCSS this has taken the form of the Ocean–Atmosphere–Ice Interactions (OAII) component of ARCSS research (page 9), which has sought to understand the Arctic marine environment and its role in climate and global change. Focusing on processes in the oceans and on fluxes from the oceans to the atmosphere, efforts that have emerged from OAII have included the Northeast Water Polynya Study (NEW), 1991–1995; Investigations of the Western Arctic (IWA), 1992–1995; the U.S./Canada Arctic Ocean Section (AOS), 1994–1997; a study on the Surface Heat Budget of the Arctic Ocean (SHEBA), 1995–2003; and the Western Arctic Shelf–Basin Interactions (SBI) program, which is in its field phase.

The SHEBA project was an effort to determine how heat fluxes that couple the atmosphere, sea ice, and ocean produce feedbacks that affect Arctic and global climate. In SHEBA, observations, conducted from a ship frozen in the Arctic pack during 1997-98, established a data set that documents these heat fluxes and related processes with unprecedented accuracy, continuity, and comprehensiveness over a full annual cycle. A major finding was that cloud radiative forcing of the surface heat budget was positive throughout the year. In the final year of SHEBA, project scientists are now applying their new data and understanding to improving local, regional, and global climate models.

The Western Arctic Shelf–Basin Interactions (SBI) project (page 24) is investigating the effects of global change on the production, cycling, and shelf–slope exchange of biogenic matter, both seasonally and spatially. It focuses on shelf, shelf break, and upper slope water mass and ecosystem modifications, material fluxes, and biogeochemical cycles as they contribute to shelf–basin interactions within the Arctic Ocean ecosystem. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the Arctic

Recent projects supported by ARCSS

ARCSS Project or Subproject Name	Acronym	Project Web Page URL
Ocean–Atmosphere–Ice Interactions	OAII	http://arcss-oaii.hpl.umces.edu/
Study of Environmental Arctic Change	SEARCH	http://psc.apl.washington.edu/search/
Western Arctic Shelf–Basin Interactions	SBI	http://sbi.utk.edu
Surface Heat Budget of the Arctic Ocean	SHEBA	http://sheba.apl.washington.edu/
U.S./Canada Arctic Ocean Section	AOS	Completed project
Investigations of the Western Arctic	IWA	Completed project
Northeast Water Polynya Study	NEW	Completed project
Land–Atmosphere–Ice Interactions	LAII	http://www.laii.uaf.edu/
Flux Study	FLUX	Completed project
Arctic Transitions in the Land–Atmosphere System	ATLAS	http://www.arts.monash.edu.au/ges/research/climate/atlas
International Tundra Experiment	ITEX	http://www.systbot.gu.se/research/itex/itex.html
Russian–American Initiative on Shelf–Land Environments in the Arctic	RAISE	http://arctic.bio.utk.edu/RAISE/index.html
Paleoenvironmental Arctic Sciences	PARCS	http://www.ngdc.noaa.gov/paleo/parcs/
Greenland Ice Sheet Project 2	GISP2	http://www.gisp2.sr.unh.edu/GISP2/
Human Dimensions of the Arctic System	HARC	http://www.arcus.org/HARC/
Pan-Arctic Community-wide Hydrological Analysis and Monitoring Program	Arctic-CHAMP	Web site pending; 18 new projects

shelves and the adjacent ocean basins. SBI therefore focuses on areas where it is believed that key processes control water mass exchange and biogeochemical cycles and where the greatest responses to climate change are expected to occur. The SBI project conducted its first field year successfully in the Bering Strait region and over the outer shelf, shelf break, and slope of the Chukchi and Beaufort Seas into the Arctic Ocean. The group completed four successful scientific missions in 2002 to the Arctic using three vessels: the USCGC *Healy*, the USCGC *Polar Star*, and the RV *Alpha Helix*. The spring cruise on the new *Healy* icebreaker was the first interdisciplinary research cruise to this region by a science vessel at this time of year. From May through September (and year-round using moorings), the group made a broad array of physical, biogeochemical, and biological measurements that is almost unprecedented in scope for the Arctic.

Another effort to emerge from OAII planning in recent years was the Study of Environmental Arctic Change (SEARCH). SEARCH has grown beyond the intellectual and institutional boundaries of the ARCSS program and is now a very broad effort with some interagency support (see *Arctic Research of the United States*, vol. 15, Fall/Winter 2001). Research is now underway on the Arctic freshwater cycle held under SEARCH auspices with support from ARCSS.

As SHEBA ends and SBI is entering its field phase, the OAII planning component has begun to envisage a future effort that would study chemical processes in the lower atmosphere. Here OAII hopes to inspire research on chemical exchanges between the ocean, ice, land, snow, and lower troposphere. This project idea draws some of its inspiration from the nascent IGBP project called the Surface Ocean Lower Atmosphere Study and would be a bold step in the direction towards true inter-compartmental studies.

The Shore

Much of the coastal Arctic lies in Russia. Recognizing this, and in view of the challenges facing much of the Russian science community, ARCSS researchers saw at an early stage that there was merit in a partnership between American and Russian scientists to study Arctic processes in the coastal zones. The Russian–American Initiative for Land–Shelf Environments in the Arctic (RAISE) was developed, and while it has always been a low-profile activity compared to the large expeditionary efforts of ARCSS, it has achieved considerable successes.

The article on RAISE on page 33 describes a number of research areas that have been successful. One important area was the launching of a number of data recovery projects involving both U.S. and Russian scientists. These data represent an important legacy that needs to be saved because they can provide important long-term records. An example of their importance is the use of historical hydrographic records from the Soviet era in syntheses of river runoff data. Recently published results found that the average annual discharge of fresh water from the major Eurasian rivers to the Arctic Ocean increased by 7% from 1936 to 1999. These discharges correlated with changes in the North Atlantic Oscillation and with increases in global mean surface air temperatures. This could mean that the large-scale change in freshwater influxes to the Arctic have important implications for ocean circulation and climate. Another example of the success of RAISE has been the proliferation of ideas into other scientific communities. Many projects inspired by RAISE involve teams of Russian and U.S. investigators who were funded recently through the Freshwater Cycle competition (see below) as part of an Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP).

Other foci in RAISE are described beginning on page 34, such as studies of the extent to which ice sheets were present at the time of the Last Glacial Maximum in northeastern Siberia and their extent in the Northern Hemisphere. As ARCSS moves towards more integrative efforts, RAISE has begun to evolve, and planning has proceeded towards a coordinated Land–Shelf Interactions (LSI) project that would focus on the pan-Arctic coastal zone and support land-, river-, and sea-based research. This emerging research effort would attempt to cross the traditional geomorphic boundaries separating marine and terrestrial lines of inquiry in Arctic system science.

The Land

In a manner complementary to OAII's, the Land–Atmosphere–Ice Interactions (LAII) component of ARCSS has sought to develop projects that improve our understanding of the interactions between land, atmosphere, and ice in the Arctic. To date, much of LAII research has focused on

Alaska and has comprised a major contribution of land-based data to U.S. global change research in the Arctic. The LAII Flux study, funded from 1993 through 1997, investigated the processes controlling the fluxes of CO_2, CH_4, water, nutrients, and energy between Arctic terrestrial ecosystems and the atmosphere. Under LAII's guidance there sprang from this effort a project called Arctic Transitions in the Land–Atmosphere System (ATLAS). ATLAS's goal was to develop an understanding of the role of the Arctic terrestrial system in global climate change by studying the interactions and feedbacks in the land–atmosphere system critical to impacts of high ecological and social importance. As ATLAS progressed, ARCSS supported a parallel effort to simulate impacts of climate change on tundra vegetation as a contribution to the International Tundra Experiment (ITEX).

Some of the key results to emerge from a decade of LAII research are highlighted in the article beginning on page 43. The Flux study and ATLAS found that the warming in the Alaskan Arctic has been associated with warming of permafrost, expansion of shrubs, and a temporary increase in CO_2 efflux. They also found that winter is a more important period of biological activity than had been previously appreciated and that vegetation changes can have a significant positive feedback to regional warming. ITEX found that experimental warming initially increases growth in most Arctic plants but that the growth response to warming diminishes over time. The Circumpolar Active Layer Monitoring (CALM) study found that the active layer depth of the permafrost responds sensitively to summer climate. Others found that spruce began to invade tundra throughout Alaska after 1850 and that spruce invasion of permafrost-affected tundra depends on the melting of permafrost in some sites. Still others found that the duration of lake ice cover (seasonal or multi-year) is a dominant control on the biogeochemistry of Arctic lakes and that this can be traced in the sediments.

LAII researchers have begun to work in the Russian Far East, and like OAII, LAII has teamed up with other ARCSS researchers to create a vision for a new effort that would follow on the heels of ATLAS and ITEX. Dubbed Pan-Arctic Cycles, Transitions, and Sustainability (PACTS), this project would explore the connected biophysical, biogeochemical, and social systems as engines of change in the Arctic by focusing on the interaction of physical and living systems.

The Past

An understanding of the past is essential to interpreting the environmental data we receive and determining where we are in the full range of past changes. An effort to develop such an understanding was first organized under the PALE (Paleoclimates from Arctic Lakes and Estuaries) and GISP2 (Greenland Ice Sheet Project Two) components, which have evolved into a more circum-Arctic Paleoenvironmental Arctic Sciences (PARCS) component. PARCS taps a community of researchers studying past climates and environments of the Arctic and sub-Arctic. This component is not uniquely an ARCSS effort but has been assembled in collaboration with the Earth System History program at the National Science Foundation.

PARCS research (page 50) aims to develop an understanding of the range of natural environmental variability in the Arctic, explore the impact and cause of "surprises" in Arctic climate system behavior, define the sensitivity of the Arctic to altered forcings, document the history and controlling mechanisms of biogeochemical cycling of nutrients and radiatively active species, and evaluate the realism of numerical models used to predict future change. PARCS does this with a focus on acquiring and analyzing paleoclimatic and paleoenvironmental records, linked with climate model experiments, to determine the causes and consequences of past warm episodes in Arctic climate. PARCS also uses paleoclimatic records of high temporal resolution to determine the natural modes of climate variability that have impacted the Arctic over the past 2000 years.

PARCS researchers have shown that there have been periods lasting from hundreds to thousands of years when the climate in the Arctic was several degrees Centigrade warmer than it has been for the past 100 years. This information is evidence of the natural range of Arctic thermal variability and gives insight into how the Arctic system responds to prolonged and pronounced warming. PARCS has also documented Arctic climatic variability and fluctuations on decade to century time scales over the last 20,000 years and has shown how some of these variations have impacted people (for example, the Norse of Greenland at the onset of the Little Ice Age). Scientists have reconstructed the postglacial history of the northern boreal forest treeline across Eurasia and have shown how the observed changes reflected changing summer temperatures due to natural variations in the Earth's orbit and the warming of the Nordic seas.

One of PARCS' goals has been to integrate paleoenvironmental records to foster the reconstruction and analysis of climatic change. To this end, PARCS has produced an online data atlas for the research community and collated paleoclimatic records of summer temperature from a variety of sources to produce a circum-Arctic record of climatic change over the past 400 years. The latter work demonstrated just how unusual late-twentieth-century warming appears to be.

The Future of ARCSS

The ARCSS program has a decade of research behind it, and the scientific results of the program have increased considerably our understanding of Arctic processes. ARCSS has employed disciplinary scientific projects in a wide array of efforts targeting portions of the Arctic system. However, it has not yet made a concerted attack at the level of the whole Arctic system nor over all time scales important to human concerns. The holistic system understanding has remained an elusive goal, not only for ARCSS but also for most of the global change programs around the world. It is a difficult task, made more so because most researchers were educated in a discipline, and even if they appreciate the needs for interdisciplinary understanding, it does not come readily or through obvious paths. The ARCSS program is taking a two-pronged approach to addressing this problem. The first is to engage more fully in the use of themes that by their very nature cut across the disciplinary boundaries imposed by science. The second approach is to assemble the thematic understanding of the system into a synthesis.

Examples of the integrative themes may be found in the flow of energy through the system, the biogeochemical cycles of carbon and nutrients and other important chemical constituents, and of course the hydrological cycle in its broadest sense, including atmospheric transport and deposition, land surface hydrology, and oceanography. Other, less-obvious themes, such as information content and flow in systems, evolution, scales of time, system memory, even system complexity, could eventually help increase our understanding of the system, but our thinking about the Arctic system is not sufficiently developed now to employ such approaches.

ARCSS has studied pieces of the energy flow story in SHEBA, and of carbon flow in ATLAS and SBI, but not yet assembled the pieces fully into a system-wide understanding. Ultimately these themes need to be linked. For example, the flow of energy is highly coupled to the hydrological cycle, and both influence the flow of carbon, though the biologically mediated component of the carbon cycle is highly regulated by organisms and thus by the information content held in the biodiversity of the system. Before we can link these themes, we need to understand more about each of them and how they cut across the various compartments of the system. To do this, ARCSS is striving now to move from the compartmentalized research mode of LAII and OAII to a thematic mode.

Integration: The Freshwater Cycle

The first major move in the direction of thematic integration is being developed through the ARCSS Freshwater Cycle effort, for which the major focus is to study the hydrologic cycle and heat balance of the Arctic and sub-Arctic atmosphere, landmass, and ocean. Scientific questions address the physical, chemical, and biogeochemical character of the Arctic freshwater system and its connections with the subpolar oceans and Arctic environmental change. The inspiration for this new focus came from the international Arctic/Sub-Arctic Ocean Fluxes (ASOF) group, the new Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) group within ARCSS, and the Study of Environmental Arctic Change (SEARCH) effort that sprang from OAII and is now coordinated across most Federal agencies working in the Arctic.

Other efforts are expected to emerge that cut across disciplinary boundaries. An example of one being discussed now in ARCSS is the Pan-Arctic Cycles, Transitions, and Sustainability (PACTS) project. Devised to explore the connected biophysical, biogeochemical, and social systems as engines of change in the terrestrial Arctic by focusing on the interaction of physical and living systems, this effort could serve as a template for a way of looking at the Arctic system with some of the less-obvious themes mentioned above, such as information flow and biodiversity. Work is anticipated in other subject areas, such as the interaction of energy flux and chemistry. Another area for significantly higher efforts is human dimensions research. Up to now, this has been a separate effort in ARCSS, but it may become much more heavily integrated into all aspects of ARCSS research.

ARCSS Synthesis

ARCSS has long had an element called Synthesis, Integration, and Modeling Studies (SIMS) that to date has been mostly a vigorous data management effort aimed at assuring the assembly, public release, and responsible archival of data (ADCC, page 79) and improving data exchange between principal investigators, particularly in field efforts and expeditions such as ATLAS, SHEBA, and SBI (JOSS, page 70). SIMS had the initial intent, however, of feeding and driving the synthetic thinking in the program, and through it ARCSS has engaged in some synthesis efforts in its individual projects (see SHEBA and ATLAS). ARCSS is now launching a new effort that will move the program towards more Arctic-system-wide synthesis.

The words "integration," "synthesis," "review," and "analysis" are often cast about almost as if they were synonymous. A review is a study and restatement of material previously studied. Analysis is the separation of a whole into its component parts; in the case of science it is an examination of a complex, its elements, and their relations. Integration is the process of forming or combining information into a functioning or unified whole, and synthesis is the combining of diverse ideas into one coherent theory or system. Analysis and integration play key roles in a synthesis. Reviews and summaries are also important building blocks towards synthesis, but the key concept in a synthesis is the struggle towards new insights and a higher level of understanding through considering research results on various facets of an overall theme.

The synthesis effort on which ARCSS is launched is still being defined, but there have already been some ideas expressed in the community. The goal being discussed is describing the whole Arctic system in an integrated fashion that would include non-ARCSS research, data sets, and people. It will certainly be a substantial research effort to collect our knowledge of the components of the Arctic system and how they fit together. The synthesis will reach down to the disciplinary level to address problems that emerge as essential to achieving the full-system understanding. The first phase of the synthesis effort is to take place in 2003.

ARCSS Program Structure

The focus of the synthesis effort will be the intellectual content of the program, not a programmatic reorganization. However, among the more valuable things likely to emerge from a synthesis will be the identification of what new research needs to be done. Thus, while the synthesis effort does not necessarily mean a major change or restructuring of the ARCSS program, it should guide the direction of the future ARCSS.

The organizational structure of ARCSS is viewed as a tool that fosters scientific learning, so if our approach to the science changes, the structure would also be expected to change. The OAII and LAII components are scheduled to end, and we expect a new structure to emerge from discussions ongoing in the ARCSS community and from the synthesis. Beyond that, there are no preconceived notions about the shape of a future ARCSS that are driving this process. It is highly likely that ARCSS will continue to study Arctic processes on the land, sea, ice, and air, that it will look to the past as well as the future, and that it will address issues relating to human dimensions.

Investigating the Arctic Marine Environment During a Period of Rapid Change

Development, Accomplishments, and Outlook for OAII

This article was prepared by the OAII Science Steering Committee, which includes Louis Codispoti, University of Maryland Center for Environmental Science; Jane Hawkey, University of Maryland Center for Environmental Science; Donald Perovich, U.S. Army Cold Regions Research and Engineering Laboratory; Leonard Barrie, World Meteorological Organization; Dennis Darby, Old Dominion University; Thomas Delworth, NOAA; Hajo Eicken, University of Alaska; Robie Macdonald, Institute of Ocean Sciences; Patricia Matrai, Bigelow Laboratory for Ocean Sciences; Astrid Ogilvie, University of Colorado; Paul Shepson, Purdue University; Michael Steele, University of Washington; David Thompson, Colorado State University; Cynthia Tynan, Woods Hole Oceanographic Institution; and John Weatherly, U.S. Army Cold Regions Research and Engineering Laboratory.

Increased concern about the Arctic system's sensitivity to global change and the role of Arctic processes in global change led to the creation of the National Science Foundation (NSF) Arctic System Science (ARCSS) program in 1988. The Ocean–Atmosphere–Ice Interactions (OAII) component of ARCSS was established in 1991 following a research community workshop held at Lake Arrowhead, California, in 1990. After this workshop the OAII Science Steering Committee (SSC) expanded its membership and, with the support of NSF, accepted responsibility for producing an ARCSS/OAII science plan. Additional component milestones included OAII all-hands meetings held in May 1997, October 1999, and November 2001. A continuing theme has been the OAII SSC's commitment to a "bottom-up" approach to developing new initiatives in which the community at large is encouraged to suggest research that relates to the marine environment of the Arctic system within the context of global change.

The timing for OAII was propitious because recent observations suggest that the Arctic is undergoing remarkable changes extending from the atmosphere into the ocean and impacting human populations and living resources. The changes continue. The last decade has been one of generally reduced ice cover. For example, the summer of 2002 had the lowest levels of ice extent and area in the passive microwave record since observation began in 1978. The observed changes are in general agreement with models suggesting that increased greenhouse gases will cause the greatest warming in the troposphere and adjacent ocean and land of the Arctic.

Recent changes must, however, be placed in the context of decadal-scale variation produced by drivers such as the Arctic Oscillation (AO), underscoring the need to build on and continue time-series observations. Indeed, recognition that the pervasive system changes noted during the past decade may be associated with a positive state of the AO has added intellectual excitement and provided theoretical underpinning to interpretation of the observed changes.

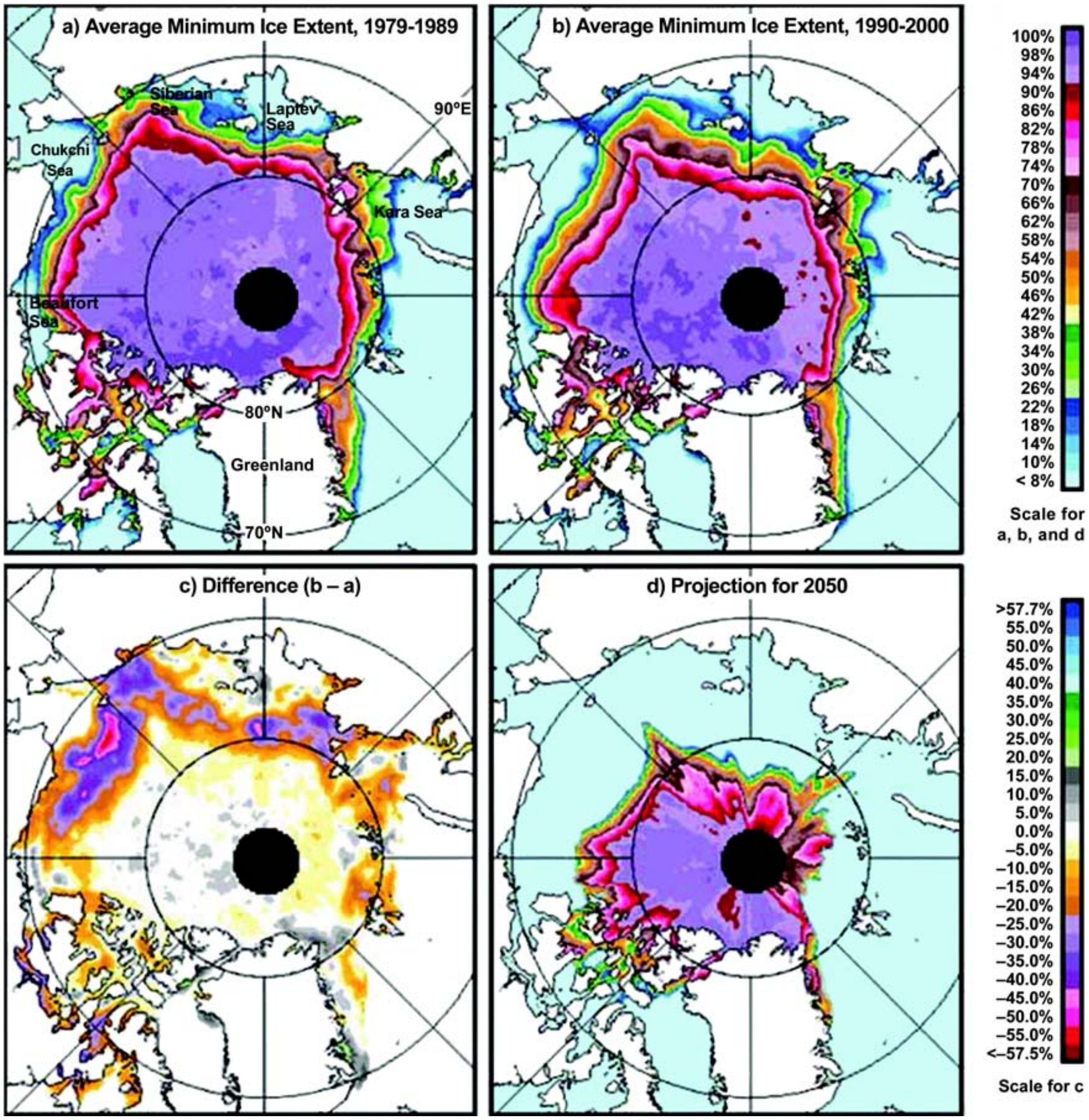
Additional positive developments in recent years include improved access for U.S. scientists arising from the construction of a research icebreaker, the USCGC *Healy*, and increased funding for Arctic logistics at NSF. Technological advances, including autonomous chemical instrumentation, improved satellites, and a new generation of autonomous and remotely operated vehicles, have also improved the outlook for Arctic research. Positive developments also include the release of formerly classified data from thousands of former Soviet Union and Western oceanographic stations in the Arctic as a result of the Gore–Chernomyrdin Commission's efforts. Finally, the aggregate international resources devoted to Arctic research may, at last, be on the increase after the lean decades of the recent past.

Completed and Ongoing OAII Research Projects

A list of OAII projects and their principal investigators is maintained on the OAII web site (http://arcss-oaii.hpl. umces.edu). These projects can be divided into two broad classes: medium to large multidisciplinary or interdisciplinary efforts and smaller, individual projects aimed at filling key gaps in priority research areas.

The following medium to large projects have been implemented under the ARCSS/OAII aegis:

- Northeast Water Polyna Study (NEW), 1991–1995;
- Investigations of the Western Arctic (IWA), 1992–1995;
- U.S./Canada Arctic Ocean Section (AOS), 1994–1997;
- Surface Heat Budget of the Arctic Ocean



Average yearly minimum perennial ice concentrations from 1979 to 1989 (a) compared with 1990–2000 (b), the differences between these two periods (c), and a projection of minimum perennial ice concentrations for 2050 (d).

(SHEBA), 1995–2003; and
- Western Arctic Shelf–Basin Interactions (SBI), 1999–2009.

In addition, OAII was instrumental in establishing the Study of Environmental Arctic Change (SEARCH), an interagency and international research program. The first SEARCH-supported research involves a collaboration with Arctic-CHAMP (Community-wide Hydrological and Analysis Program), which is supported by ARCSS, and the Arctic and Subarctic Ocean Flux (ASOF) program, which is supported by the European Commission. This research will include the establishment of an instrument array at the entrances to the Arctic Ocean for monitoring ocean and hydrological fluxes, which are an important determinant of the global "thermohaline" (overturning) circulation and the ability of the ocean to sequester atmospheric carbon dioxide.

Although the five medium to large OAII projects received major support from ARCSS/OAII, they were collaborative efforts that involved other nations and other government agencies as well.

Northeast Water Project

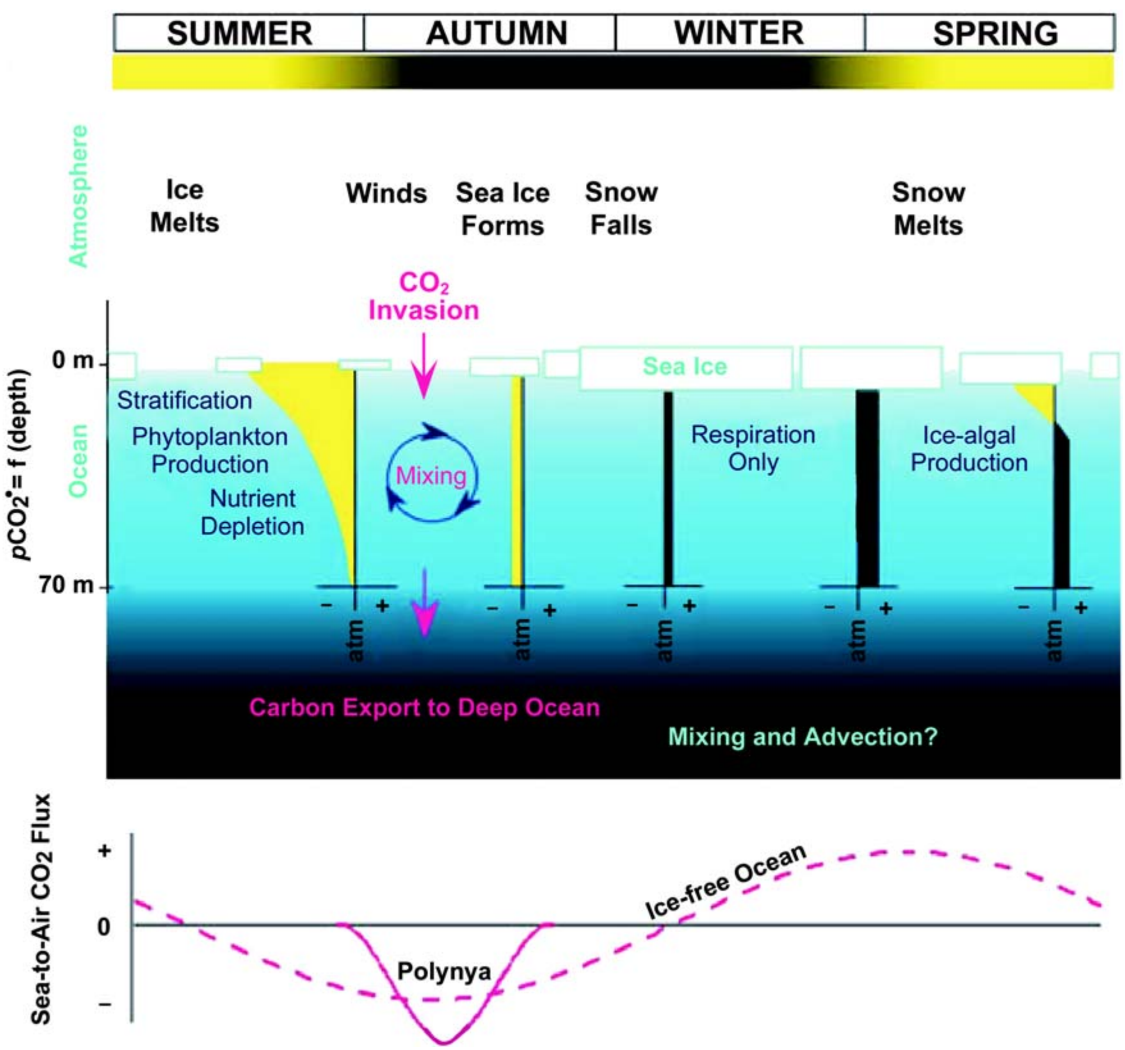
The Northeast Water Polynya Study (NEW) examined a polynya located on the continental shelf off northeast Greenland at high latitude (about 80°N). Much of the focus was on how carbon is processed in a seasonally open water area, with a view towards enhancing predictions of how the ecosystem and various biological processes would change if warming increased the amount of open water at high northern latitudes.

This first OAII project was inherently international, with the Arctic Ocean Science Board endorsing it as the first major project of the International Arctic Polynya Program and with the first expedition in 1991 led by Germany. Thus, in addition to U.S. scientists receiving support from OAII, many other researchers were supported by Canada, Denmark, Germany, Greenland, Poland, and several other countries. Research platforms included Germany's *Polarstern* and the U.S. Coast Guard's *Polar Sea.*

The OAII-supported results shed considerable new light on primary and secondary productivity, carbon dioxide fluxes, carbon/nutrient ratios, pelagic–benthic coupling in the NEW polynya, and biogeochemical cycling in the NEW polynya. For example, the results represented the first assessment of new primary production throughout an entire season in the Arctic. A surprising result was that advection of zooplankton onto the shelf in the polynya was low, resulting in a low abundance of herbivorous zooplankton. Comparison of these results with later work in another high-Arctic polynya, the North Water polynya in northern Baffin Bay, suggests that the absence of close coupling between phytoplankton and zooplankton in the NEW polynya helps to account for its lower overall productivity. NEW investigators also suggested, based on considerations of physical, chemical, and biological processes, that high-latitude polynyas are efficient sinks for atmospheric carbon dioxide.

Data on physical variables and particle fluxes were successfully recovered from four moorings, providing the first suite of year-round oceanographic observations from the NEW polynya. These moorings documented features such as a wintertime mixing event that helped to replenish nutrients and reset the ecosystem for the higher

A conceptual model for carbon cycling in the NEW polynya suggesting that it is relatively efficient at sequestering atmospheric carbon dioxide.



productivity observed at most trophic levels during 1993.

Many additional NEW results are reported in a special volume of the *Journal of Geophysical Research* (vol. 100, no. C3, 1995) and in a special volume of the *Journal of Marine Systems*. Note that during the summer of 2002 the ice cover in the Arctic Ocean in general and in the NEW study region was markedly reduced, suggesting that the NEW investigators were on the right track when they suggested the need to learn more about high-latitude open water ecosystems. This line of research continues with the implementation of additional international polynya projects (http://www.fsg.ulaval.ca/giroq/now/wel.htm).

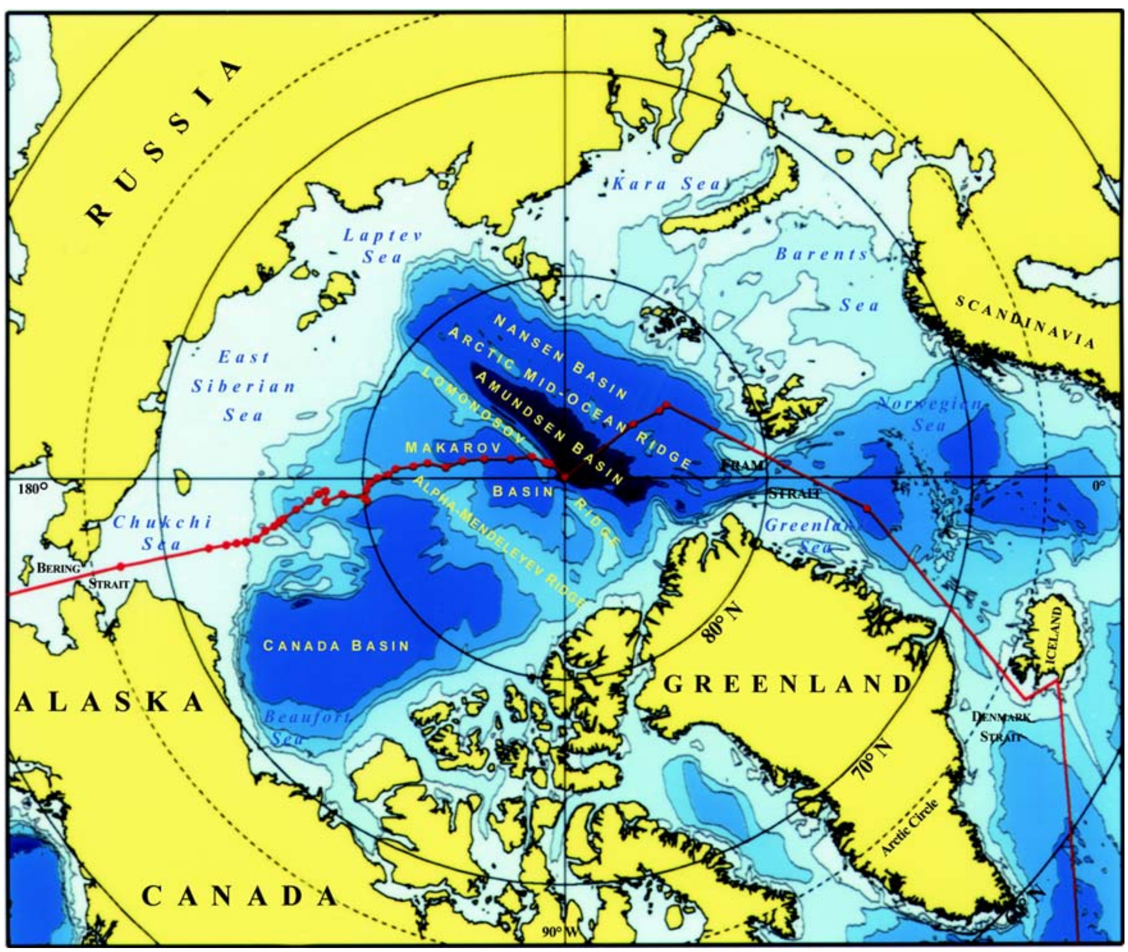
Investigations of the Western Arctic Project

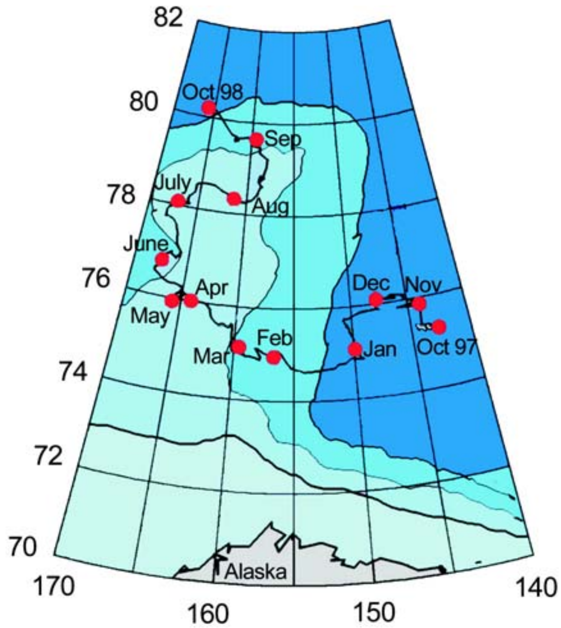
The Investigations of the Western Arctic (IWA) experiment was known initially as the Western Arctic Mooring (WAM) experiment. Under the aegis of this project, an international effort to continue the monitoring of transports through Bering Strait and the Barrow Canyon region has been maintained. Recently the temperature, salinity, and current sensors have been supplemented by water sampling devices and by in-situ nutrient analyzers. The results have helped to document a significant warming and freshening of the Bering Strait inflow to the Arctic Ocean, which may be accompanied by a change in the nutrient inputs. For example, maximum salinities in the inflow have decreased by approximately 1.5 psu. IWA also provided new information on the formation and transport of halocline waters formed in the northeastern Chukchi Sea and on the flux and dispersal of fresh water carried onto this shelf in the Siberian Coastal Current. This program also documented water mass transports in Barrow Canyon and their response to the wind regime. Several expeditions to the Bering–Chukchi–Beaufort region were also supported under the IWA aegis.

Arctic Ocean Section

The 1994 Arctic Ocean Section (AOS) project was an international program that received major

Station location track for the 1994 Arctic Ocean Section (AOS) expedition that crossed the Canada Basin.





The drift track taken by the Surface Heat Budget of the Arctic Ocean (SHEBA) ice station, 2 October 1997 to 9 October 1998.

support from the United States and Canada. The OAII program and the Office of Naval Research (ONR) provided support for U.S. participants. This effort produced the first comprehensive treatment of the properties of the Canada Basin, including pollutants and associated biological processes. It also helped to document how major changes in the hydrography of the Arctic Ocean have been unfolding since the late 1980s. The AOS results suggested that many previous estimates of the biological productivity of the Polar Basin were too low, partly because of insufficient recognition of the role of ice algae. Furthermore, heterotrophic microbes were found to be far more active in these perennially cold waters than previously thought. This project was comprehensive and included coordinated observations from two icebreakers on geological structure, biogeochemical cycling in Canada Basin sediments, tracer chemistry, biogeochemical cycling, the "microbial loop" etc. Although many of the results are reviewed in a special issue of *Deep-Sea Research* (vol. 44, no. 8, 1997), results continue to be published in a variety of journals.

Surface Heat and Radiation Budget of the Arctic Ocean

The SHEBA (Surface Heat Budget of the Arctic Ocean) project is governed by two broad goals:

- Enhancing our understanding of the ice–albedo and cloud–radiation feedback mechanisms, and
- Using this understanding to improve the treatment of sea ice in large-scale models.

The centerpiece of the SHEBA program was a year-long international and interdisciplinary field experiment. On 2 October 1997 the Canadian Coast Guard icebreaker *Des Groseilliers* was frozen into the pack ice of the Beaufort Sea, the first such science platform "besetting" in over a century.

For the next year this ship drifted with the ice pack as an interdisciplinary team of researchers made a comprehensive suite of measurements of the atmosphere, ice, and ocean. These measurements included profile properties of the atmosphere, cloud fraction and properties, atmospheric boundary layer, surface radiation fluxes, albedo, snow properties, ice mass balance, ice stress, ocean boundary layer, and thermohaline structure of the upper ocean. Because of the large variability of surface properties, SHEBA measurements were made at multiple sampling sites and in spatial surveys using aircraft, submarines, and satellite remote sensing. This was done to sample a region large enough to represent the surface "footprint" of a single grid cell in a high-resolution climate model. The "besetting" of the *Des Groseilliers* also presented a remarkable opportunity to collect invaluable data on a full year's cycle of biology and hydrology in the upper ocean under the auspices of the Joint Ocean Ice Study (JOIS), which was organized by and received major support from Canada.

The SHEBA experiment further documented the thinning of the ice cover in the Arctic and the freshening of the surface layers and shed new light on the roles of atmospheric moisture, leads, and melt ponds. Data collected during the SHEBA/JOIS drift also revealed that freshwater runoff has been stored in the Canada Basin in response to the highly positive AO conditions during the 1990s, leading SHEBA researchers to suggest that hydrological feedback may be as important as ice–albedo feedback in changing the Arctic's upper ocean. This freshening also seems to have had a dramatic impact on the biological structure of ice communities. Other biological studies conducted during the SHEBA drift documented the seasonal cycles of zooplankton, heterotrophic microbes, and community respiration and production. The SHEBA biological results generally confirm the findings of the AOS project, which found that canonical estimates of productivity within the permanent ice pack are too low, but that microbial activity was lower, suggesting significant temporal variability on the interannual (or shorter) time scale.

The SHEBA field work was quite successful, in large part because of the interdisciplinary approach and cooperative spirit that developed aboard the *Des Groseilliers*. SHEBA results have been disseminated in many conference presentations and journal articles and in a special section of the *Journal of Geophysical Research* (October, 2002). SHEBA is now in Phase III, its final phase, which will officially continue through 2003. This phase emphasizes synthesis, analysis, and modeling of the data from the Phase II field experiment. While the SHEBA program officially ends in 2003, the analysis of the data set and its assimilation into large-scale models will continue into the future. The year-long observational data set is a key legacy of the SHEBA program. These data are available through the Joint Office of Science Support, University Corporation for Atmospheric Research (http://www.joss.ucar.edu/cgi-bin/codiac/projs?SHEBA). The data will be archived for long-term access at the Arctic System Science Data Coordination Center, National Snow and Ice Data Center (http://arcss.colorado.edu). More information on SHEBA may be found at http://sheba.apl.washington.edu and in companion articles in this issue of *Arctic Research of the United States.*

Western Arctic Shelf–Basin Interactions Project

The Western Arctic Shelf–Basin Interactions (SBI) project is in Phase II of three planned phases. This project focuses on biogeochemical cycling in the outer shelf and upper slope portions of the Chukchi and Beaufort Seas and their interactions with the Arctic Ocean. SBI is, in part, a response to the recognition that the extensive Arctic shelves are crucial to determining the character of the Arctic marine ecosystem and to the maintenance of the halocline, the salt gradient in the upper 200 m that is so important to the dynamics, thermodynamics, and ecosystem structure of the Arctic Ocean proper. While we understand the importance of these processes and know that some of them are undergoing significant change, the shelves and slopes of the Arctic are poorly sampled, with even seasonally resolved data from these shelves being sparse and in many cases absent. Thus, we lack a mechanistic understanding sufficient to enable us to develop tools for predicting change in this region. At the same time the recent changes observed in the Arctic system may be having significant impacts. For example, accelerated coastal erosion may be increasing the material fluxes onto the shelves of the Arctic Ocean. In addition, the changes in characteristics of the Bering Strait inflow that have been noted previously, if prolonged, could have a significant influence on the thermohaline structure of the Arctic Ocean and on nutrient cycling.

SBI Phase I was devoted to retrospective data analysis, modeling, and field experiments that were an appropriate prelude to the main field effort that is occurring during Phase II. One interesting result arising from the Phase I paleoceanography studies was evidence for rapid climatic change in the western Arctic that is not reflected in the records from the Greenland ice cores. SBI Phase II began in earnest during the spring and summer of 2002 with two major process cruises on the Coast Guard research icebreaker *Healy* and with mooring/hydrography cruises on the Coast Guard icebreaker *Polar Star* and the University of Alaska's *Alpha Helix*. All cruises went well and provided important new data on the plumes of bioactive material originating on the outer shelf and slope and on the biological and physical processes that produce and modify this transport of bioactive material to the interior of the Arctic Ocean. The Phase II data are in the early stages of analysis, but it is already clear that these data will provide important new insights into the variable timing of phytoplankton blooms in the study region, the regeneration of nutrients over the outer shelf, and the effect of the halocline in restricting the biological signals originating over the shelf largely to the upper 250 m in the adjacent Arctic Ocean.

Additional SBI information is available in a separate article in this issue of *Arctic Research of the United States* and on the SBI web site (http://sbi.utk.edu).

Study of Environmental Arctic Change

The Study of Environmental Arctic Change (SEARCH) originated within OAII and was initially motivated by the striking changes observed in the Arctic Ocean's structure and circulation beginning in the early 1990s. The frontal boundary between the eastern and western halocline types had migrated from roughly over the Lomonosov Ridge to roughly parallel to the

Alpha and Mendeleyev Ridges, and cores of relatively warm Atlantic water have been observed over the Lomonosov and Mendeleyev Ridges.

It soon became apparent, however, that these maritime changes had counterparts on the land and in the atmosphere. For example, there has been a trend of decreasing atmospheric pressure over the Arctic Basin, air temperature has risen over the Russian Arctic, and permafrost is thawing in many regions. In addition, the need to compare the present-day changes with the paleo record is obvious. Thus, SEARCH has evolved into a program that will transcend the ARCSS components and that should help propel us into a more interdisciplinary approach to investigating the Arctic system in the context of global change.

The SEARCH project has a Scientific Steering Committee that collaborates with an interagency working group formed under the auspices of the U.S. Interagency Arctic Research Policy Committee (IARPC). This working group includes EPA, the Smithsonian Institution, NSF, NOAA, NASA, DOD, and DOI. A SEARCH science plan has been published, along with an implementation plan that includes input from all ARCSS components. SEARCH research has begun to support research projects involving the Arctic system's hydrologic cycle and the North Atlantic overturning circulation. More information on SEARCH can be found at http://psc.apl.washington.edu/search/index.html.

Synthesis, Integration, and Modeling

Because the ARCSS program focuses on the Arctic system, Synthesis, Integration, and Modeling (SIM) includes integral activities within OAII. For example, Phase I of the SBI experiment included physical and biological models that should help inform the Phase II field work. An early response to the need for SIM was the convening of an OAII modeling workshop. OAII investigators also participated in an ARCSS modeling workshop in 1996. A partial list of OAII simulation, integration, and modeling results includes:

- A Lagrangian model of the Bering and Chukchi Sea ecosystem that agreed well with observations and suggested a significant role for dissolved organic carbon storage in the Arctic halocline;
- A study of the thermodynamics of the Arctic mixed layer suggesting the importance of solar radiation entering the ocean through leads and thin ice;
- Modeling studies of the thermodynamic interactions between the atmosphere and sea ice that suggest that the ice thickness in the central Arctic may undergo large (approximately 1 m) fluctuations on time scales of 1–15 years in response to varying atmospheric heat flux;
- Models of dense water formation and transport on and off Arctic shelves and their relation to halocline maintenance, showing the potential importance of small baroclinic eddies (15–25 km in diameter), the influence of alongshelf currents and canyons, and the effects of ambient stratification and shelfbreak topography;
- Modeling of convection with thermobaric effects, indicating that dense bottom plumes flowing out of Denmark Strait can be detected by remote sensing;
- A comparison between numerical models and data that suggests that existing models do a poor job of simulating freezing and melting along the North American coastline, perhaps because of large interannual variability;
- A coupled ice–ocean model suggesting that a realistic atmospheric forcing field for the 1979–1993 period, which may change in response to the Arctic Oscillation or North Atlantic Oscillation, can account for the recently observed dramatic, large-scale changes in sea ice and oceanic conditions;
- Analysis of global climate model simulations suggesting that the Arctic Oscillation can be responsible for much of the recently observed trends in sea ice and in the Arctic Ocean and that this type of variability is present in paleoclimatic data from the Arctic;
- Improvement in the Community Climate System Model relating to the effects of cloud water on solar and longwave radiation based on measurements obtained during SHEBA; and
- Incorporation of sea ice albedos measured during SHEBA into the new sea ice component of the Community Climate System Model, which will be used for climate change scenarios developed for the IPCC (Intergovernmental Panel on Climate Change).

Since ARCSS/OAII data are available to all approximately two years after collection and are archived at the National Snow and Ice Data Center, OAII results are likely to resonate in models long after the projects that produced these results have ended.

Priorities for Future OAII Research

Chemical Exchanges Between the Land, Surface Ocean, Ice, Snowpack, and Lower Troposphere

To date, OAII has not supported a project focused on interactions between surface processes, the biosphere, and the atmosphere. However, it is now clear that fluxes of trace gases, aerosols and aerosol precursors, and pollutants between the upper Arctic Ocean and the overlying troposphere can significantly impact both the Arctic atmospheric composition and the underlying biosphere. This gap has been recognized and discussed for several years at a variety of OAII meetings, and some research relating to these topics has been conducted by international partners during OAII-sponsored programs. Major gaps in our knowledge of these topics remain, however, and OAII is now poised to begin a research program. To develop community consensus and to explore and define research priorities, a workshop called "Changing Environmental Controls on Coupled Chemical Exchange between the Ocean, Ice, and Atmosphere in the Arctic" was held in November 2002 at Purdue University. The workshop brought together 24 investigators to identify prospective collaborators, determine and evaluate scientific priorities, creatively address logistics, and make recommendations for a coordinated study.

The workshop participants recommended a coordinated field, laboratory, and modeling study of air–surface exchange processes in the Arctic, named Ocean–Sea Ice–Snowpack–Atmosphere Interactions Research (tentatively OASIS). This project would emphasize chemical coupling between these reservoirs and would include the following objectives:

- Understanding the solar influence on physical, chemical, and biologically mediated exchange processes involving halogens, nitric oxide, ozone, volatile organic compounds, persistent organic pollutants, mercury, sulphur species, and carbon dioxide in the Arctic and their links to climate change;
- Understanding the influence of OASIS exchange processes on physical and radiative characteristics of clouds and hence on climate;
- Determining the impact of past changes in environmental pollution on OASIS exchange processes as part of the development of a capability to predict future changes;
- Determining the impact of changes in ice cover characteristics and temperature on chemical OASIS exchange and the associated feedbacks on climate; and
- Determining the impact of chemical OASIS exchange on tropospheric chemistry and climate as well as on the surface and biosphere and their feedbacks.

A workshop summary presentation is available at http://www.chem.purdue.edu/arctic/ArcticWorkshop.htm. This site will be periodically updated as an OASIS science plan and management structure are developed.

Nearshore Processes

As a partial response to the need for intensified interdisciplinary research within ARCSS, the OAII all-hands meeting held in Salt Lake City during November 2001 was concurrent with meetings of the Land–Atmosphere–Ice Interactions (LAII) component of ARCSS and with the ARCSS-sponsored Russian–American Initiative for Land–Shelf Environments in the Arctic (RAISE). All three groups recognized the importance of studying the coasts and adjacent inner shelves of the Arctic system, where most of the human populations and living resources are located. This zone is already heavily impacted by warming (resulting in coastal erosion and permafrost warming, for example) and by energy development.

Accordingly a steering group has been formed and an initial document outlining the science issues involved in a Land–Shelf Interactions (LSI) project has been distributed and discussed by the OAII, LAII, and RAISE steering committees at a joint meeting held in San Francisco in December 2002. This plan is now being considered by the ARCSS Advisory Committee. The overall objective is to develop a coordinated, interdisciplinary research program that would support land-, river-, and sea-based researchers who would focus on the impacts of climate change on human and biological communities and related physical and chemical systems in the coastal and nearshore regions of the Arctic system. The questions of interest to LSI include the following:

- What are the impacts of coastal erosion?
- What is the fate of the peat and dissolved organic matter transported to the nearshore environment by coastal erosion and runoff?
- How important are trace gas releases from thawing permafrost?
- How may changing runoff patterns influence the coastal–nearshore system?
- How has the coastal–nearshore zone been influenced by previous climate change?

Because of the concentration of human populations and resources in the coastal and nearshore environment, LSI will have a strong contingent of researchers interested in the Human Dimensions of the Arctic System (HARC). The HARC component of ARCSS has already hosted an online workshop dealing with LSI-related issues. During this workshop it was recognized that changes in oceanographic conditions, such as the sea ice regime and the extent of brackish water, may have a significant impact on the concentration and availability of living resources. Additional information on LSI (including a draft science plan) is available at the RAISE/LSI web site (http://arctic.bio.utk.edu/RAISE/index.html).

OAII Outreach Activities

Although this report emphasizes OAII research, it is important to note that the scientific activities went hand in hand with significant outreach efforts. These included articles and programs in the national and local media presenting OAII research to the general public. For example, reporters participated in the SHEBA drift experiment and in the SBI fieldwork, resulting in coverage on national TV and radio, as well as a large number of print articles. K–12 teachers have also participated in OAII research through NSF's Teachers Experiencing Antarctica and the Arctic (TEA) program. OAII researchers have developed educational web sites, educational games, and contests dealing with the Arctic, assisted with K–12 curriculum development, and made many presentations to K–12 students and the public at large. In addition, to facilitate and stimulate outreach, examples of outreach activities are provided on the OAII website (http://arcss-oaii.hpl.umces. edu).

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SHEBA: The Surface Heat Budget of the Arctic Ocean

This article was prepared by Donald K. Perovich, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire; Richard C. Moritz, Polar Science Center, University of Washington, Seattle; and and John Weatherly, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Central to almost all aspects of Arctic system science is the problem of projecting the variations of Arctic climate during the next 100 years and beyond. Such projections are based on simulations performed with global numerical models of the climate system that represent the atmosphere, the oceans, land surfaces, the snow cover, and the sea ice cover. These simulations indicate that physical processes occurring in the Arctic ocean–atmosphere–ice system produce climate feedback mechanisms involving thermodynamic coupling of the sea ice, snow cover, and Arctic clouds. Two key processes are the ice–albedo and cloud–radiation feedback mechanisms. These feedbacks strongly influence the simulated Arctic climate; however, there is wide variation in the response of different climate models to perturbations, such as enhanced atmospheric greenhouse gases. Through its effect on the circulation of the atmosphere and ocean, the high sensitivity of the Arctic climate extends the uncertainty surrounding future climate scenarios to hemispheric and global scales.

The uncertainties associated with Arctic climate sensitivity have long been recognized by the Arctic research community. The combination of the importance of the Arctic sea ice cover to climate and the uncertainties of how to treat the sea ice cover led directly to SHEBA: the Surface Heat Budget of the Arctic Ocean. SHEBA is a large, interdisciplinary project that was developed through several workshops and reports. SHEBA was governed by two broad goals: understand the ice–albedo and cloud–radiation feedback mechanisms and use that understanding to improve the treatment of the Arctic in large-scale climate models. The SHEBA project was sponsored _jointly by the National Science Foundation's Office of Polar Programs Arctic System Science program and the Office of Naval Research's High Latitude Dynamics program. From a programmatic perspective, it was critical that SHEBA be an interdisciplinary experiment: one where a diverse group of researchers come together, each bringing their own particular expertise, to work on the common goals of the program. Achieving this interdisciplinary teamwork was one of the major successes of SHEBA.

Background

The ice–albedo feedback is a straightforward concept. The albedo is simply the fraction of the incoming sunlight that is reflected. Interestingly, snow has the largest albedo of any naturally occurring material on earth, while water has one of the smallest. The snow-covered sea ice reflects most (about 80%) but not all of the incident sunlight. This absorbed sunlight leads to melting, which in turn lowers the albedo, resulting in more absorbed sunlight, increasing melting, and the process continues. The ice–albedo feedback has been understood qualitatively for over 100 years. The challenge for SHEBA was to quantitatively define it in a form suitable for large-scale climate models. The ice–albedo relationship is significant because it is a positive feedback, so a small change can be amplified into a large difference.

The cloud–radiation feedback is more complex. During the long night of the Arctic winter, clouds act as a blanket, trapping thermal radiation and warming the surface. However, in summer, the sun is up, and clouds have two opposing effects on the surface heat budget: again, they act as a blanket, but they also act as an umbrella, reducing the amount of sunlight and cooling the surface. Prior to SHEBA we did not know even qualitatively— let alone quantitatively—which of these cloud effects is stronger, or whether Arctic cloud variables tend to increase or decrease in response to changes in the surface heat budget. Knowledge of these relationships is essential to evaluating the net interaction between Arctic clouds and the ice cover.

Ice Station SHEBA near the beginning of the drift on 28 October 1997. The Canadian Coast Guard Icebreaker Des Groseilliers *served as a base of operations for the field experiment. The huts housed scientific equipment and logistical supplies.*

The SHEBA program was divided into three phases. The first phase was directed towards analyzing existing data sets, formulating models, and determining the key knowledge gaps. During Phase 1 it became clear that the major obstacle to understanding the feedback mechanisms was a lack of a comprehensive, integrated set of observations, and most importantly a set of observations that extended over an entire annual cycle. This identified need led directly to the centerpiece of Phase 2: the year-long drift of Ice Station SHEBA. Phase 3 is currently underway and is directed towards analysis of the field results and model development.

Ice Station SHEBA

On 2 October 1997, the Canadian Coast Guard icebreaker *Des Groseilliers* stopped in the middle of an ice floe in the Arctic Ocean, beginning the year-long drift of Ice Station SHEBA. For the next 12 months, until 11 October 1998, Ice Station SHEBA drifted with the pack ice from 75°N, 142°W to 80°N, 162°W. At any given time, there were 20–50 researchers at Ice Station SHEBA. During the year over 200 researchers participated in the field campaign, spending anywhere from just a few days to the entire year.

Conducting a year-long sea ice experiment provided daunting scientific and logistic challenges: low temperatures, high winds, ice breakup, demanding instruments, and polar bears. It was truly a unique opportunity to observe with our eyes, as well as our instruments, the changes that a sea ice cover undergoes over the course of an annual cycle. For much of the year the ice was covered by snow. The average snow depth was about 35 cm, and the surface was uniform and had a large albedo. This was all changed by the onset of melt. The surface was transformed into a highly variegated mixture of bare ice, melt ponds, and open water, and the albedo decreased substantially.

Of course, the field program was much more than visual observations and personal impressions. There was an intense measurement program designed to obtain a complete, integrated time series of every possible variable defining the state of the "SHEBA column" over an entire annual cycle. This column is an imaginary cylinder stretching from the top of the atmosphere through the ice into the upper ocean. Observations included longwave and shortwave radiative fluxes; the turbulent fluxes of latent and sensible heat; cloud height, thickness, phase, and properties; energy exchange in the boundary layers of the atmosphere and ocean; snow depth and ice thickness; and upper ocean salinity, temperature, and currents. This year-long, integrated data set provides a test bed for exploring the feedback mechanisms and for model development.

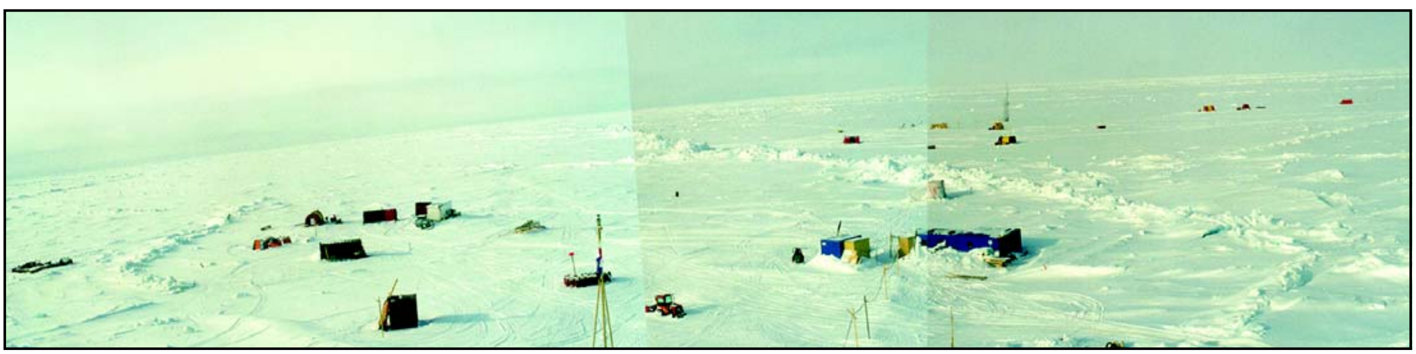
Results

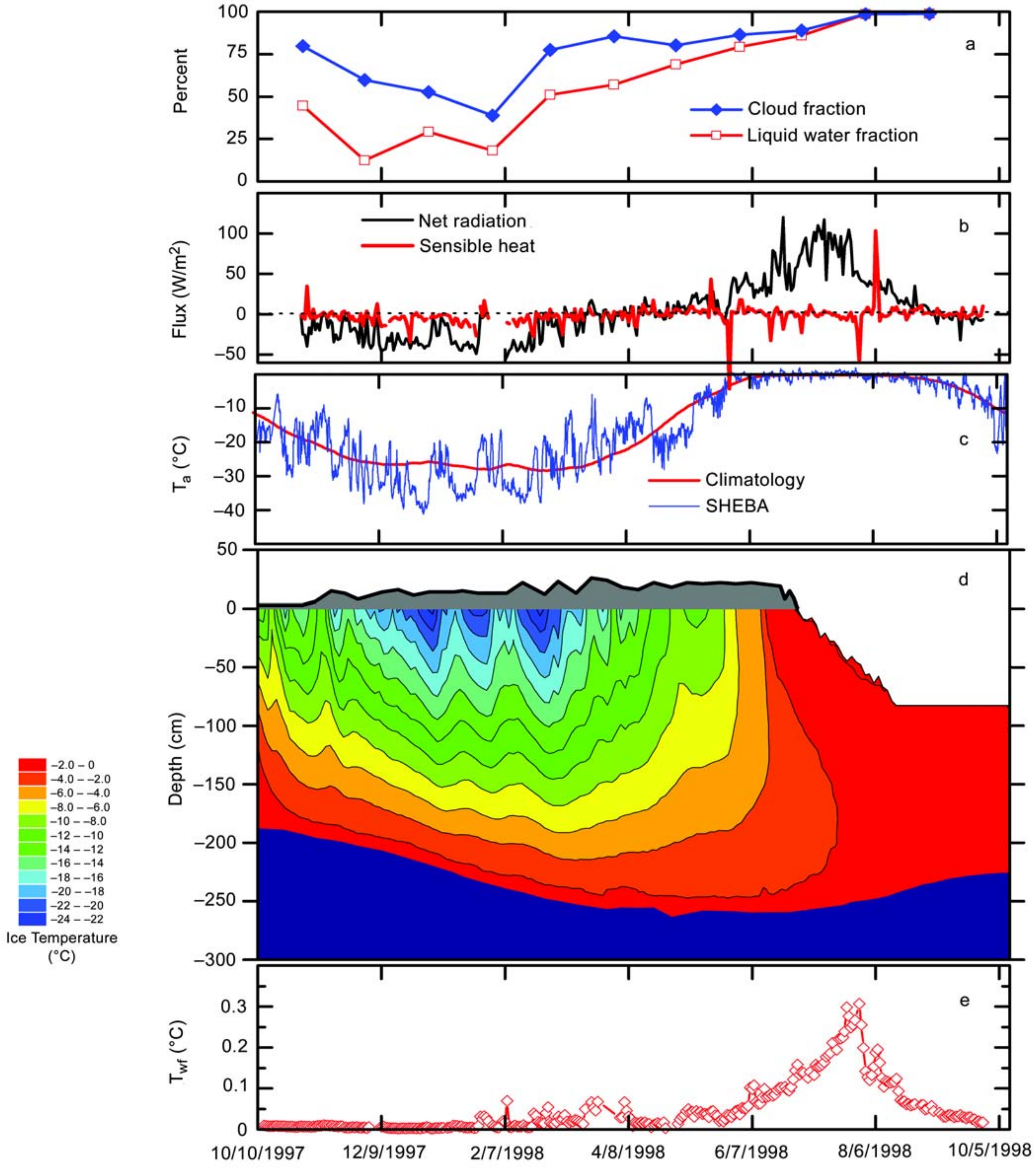
Cloud fraction and occurrence of liquid water in the cloud were monitored using a combination of radar and lidar. Clouds were pervasive at SHEBA. Even in midwinter the sky was overcast at least 40% of the time, and in the summer there was almost continuous overcast. There was cloud liquid water present throughout the year, with liquid fractions of nearly 100% in summer and approximately 20% in winter.

The net surface radiation flux (that is, the net surface longwave plus net surface shortwave irradiance) was negative during the winter. In winter there was little to no incident solar radiation, and the radiation flux was dominated by longwave radiation. The large changes in the radiative flux were due to clouds. The net radiative flux was large and negative under clear-sky or high-cloud conditions. Under low clouds the net radiation was much smaller in magnitude. By April the increasing contribution of solar radiation resulted in the net radiative flux shifting from negative to positive. The net radiative flux reached a maximum of 130 W/m^2 in mid-July, when incident shortwave radiation was large, the surface albedo was relatively small, and there were low clouds present with warm air aloft. This confluence of factors resulted in both the net shortwave and the net longwave fluxes being positive.

The effect of changes in winter cloud conditions was also manifested in surface temperatures, with the low-cloud regime resulting in surface temperatures 10–20°C higher than the clear-sky or high-cloud regime. The annual average air temperature at Ice Station SHEBA was only 0.6°C lower than the regional climatological average temperature. There were, however, several differences in the annual cycle of temperature. Comparing the climatological and SHEBA air

Views from the bridge of the CCGC Des Groseilliers *on 17 April 1998 and 8 August 1998.*





Selected annual cycle time series results from the SHEBA column: a) cloud fraction and occurrence of liquid water in the cloud; b) daily averaged net radiation fluxes; c) Ice Station SHEBA and climatological air temperatures; d) snow depth (gray-shaded area), ice thickness (blue-red and red-white boundaries), and ice temperature (color contours); and e) elevation of ocean mixed layer temperature above the freezing point.

temperature time series shows that the SHEBA year was relatively cool in winter and warm in spring. Most pronounced was the difference in the summer melt season. The SHEBA melt season was quite long, lasting almost 80 days, compared to an average of only 55 days. This long melt season had significant consequences for the ice mass balance.

The mass balance was measured at more than 100 sites. The snowpack accumulated slowly over nine months and then melted rapidly in only a few weeks in June. Rain on 29 May 1998 marked the start of the surface melt season. The annual cycle of ice thickness was similar at all sites, though there was considerable spatial variability in the magnitude of the mass balance. The cold front propagated down into the ice during fall, finally initiating bottom growth in November. There was a steady increase in ice thickness throughout the winter, with a gradual tapering in the spring. In the summer the ice was isothermal at its melting point. On average at SHEBA there were about 0.5 m of ice growth in winter and 0.64 m of surface melt and 0.62 m of bottom melt in summer. There was a substantial net thinning of the ice at the SHEBA measurement sites of 0.75 m during the SHEBA year.

The upper oceanic mixed layer was close to the freezing point for much of the year from fall through winter into late spring. With the onset of summer melt, the combination of a decrease in ice albedo and an increase in the area of open water and ponded ice allowed significant amounts of sunlight to be absorbed in the upper ocean. This solar energy resulted in warming that continued through the summer, with the mixed layer reaching a peak temperature of 0.3°C in late July. After this, a storm caused significant ice motion and mixing of the water. The storm-associated mixing resulted in the increased ice bottom melt and a decrease in water temperature.

The analysis of the field data has provided many insights into the ice–albedo and cloud–radiation feedbacks. The seasonal evolution of areal surface albedo had five distinct phases, corresponding to the following surface conditions: dry snow, melting snow, pond formation, pond evolution, and fall freeze-up. To model the seasonal evolution of albedo accurately, it is necessary to accurately determine the timing of these transitions and to know the relative areas of ice, ponds, and open water. For the relatively low, wet cloud cover present at Ice Station SHEBA during the summer of 1998, the cloud–radiation feedback was positive. The net effect of the clouds was warming and enhanced surface ablation.

The SHEBA data set is fundamental to the legacy of the SHEBA field experiment. The analysis of the Phase 2 field results has been completed, and the results are archived at http://www. joss.ucar.edu/cgi-bin/codiac/projs?SHEBA. These data are available for the use of all interested researchers.

Modeling

Some of the smallest-scale modeling is focused on the interaction of radiation and sea ice. A model of radiative transfer in sea ice has been developed that uses the physical properties of ice measured at SHEBA and computes the radiation profile through an ice column. Radiation measurements through sea ice at SHEBA suggest that the horizontal scattering of light in sea ice can play a significant role in the light transmitted around and through melt ponds. The column radiation model can act as a tool to improve the treatment of radiation in large-scale models to account for melt ponds and impurities in ice such as sediment, brine, and bubbles.

Modeling of the upper ocean has provided insight and generated questions about some of the unique phenomena observed during SHEBA. A steady warming of the upper ocean was measured in June 1998, with temperatures elevated above freezing. The solar radiation is the dominant heat source to the surface; it was not clear how this energy was reaching the upper ocean. The fraction of open water was below 5% in June, which would absorb a relatively small amount of energy. The diurnal cycle of the heating was synchronous with the insolation, so a more remote heat source was ruled out. A model of the upper ocean heat balance suggests that 8% of the incoming solar radiation at the surface was absorbed in the ocean, but it is not yet clear how this energy was transmitted through the ice cover.

Parameterizing the atmospheric turbulent fluxes over sea ice has led to a new formulation of the drag coefficient appropriate for large-scale models. The high-frequency turbulence data from SHEBA show that as the ice surface melts in summer, and ice concentration decreases, the surface becomes rougher and the drag coefficient increases, peaking at about 60% ice concentration. The vertical edge effects from melting floes and the disintegrating ice pack appear to dominate the drag effect in summer.

Modeling the vertical column of air, ice, and upper ocean following the SHEBA camp (the SHEBA column) has led to improvements in global climate models, such as the parameterization of cloud liquid water content in the Community Climate System Model (CCSM). Using the lidar cloud measurements, the atmosphere profiles from balloonsonde data, and surface fluxes from the meteorology tower, the column model showed a bias of –20 W/m^2 in the total longwave and shortwave radiation at the surface, resulting from the cloud-radiation scheme in the CCSM. Correcting the radiative path for the cloud liquid water amounts found in SHEBA reduced this bias significantly. The impact of this correction on global CCSM simulations has been a significant improvement in the surface radiation in the Arctic, leading to more realistic ice and snow cover in the model.

Sea ice models of both the thermodynamics and dynamics observed during SHEBA have shown the importance of processes that have yet to be incorporated into global climate models. The thermodynamic sea ice model used in the CCSM has been used to simulate the cycle of growth and melt observed at SHEBA. Using the meteorological observations, including radiation, precipitation, and the upper ocean temperatures, the CCSM ice model simulates the growth and melt of ice without melt ponds to within an average of 5 cm. The evolution of albedo that reflects the appearance and growth of melt ponds is not yet included in the CCSM ice model, so the modeled albedo shows a sharp transition to summer melt. The lateral melting and the reduction in ice concentration during summer are highly dependent on the formulation of the ice–ocean heat flux and the model's formulation of dynamic lead opening. The dynamic forcing on the ice in summer creates open water leads and allows greater solar energy input to the upper ocean. This energy, in turn, creates greater lateral ice ablation and more open water, which is the local-scale ice–albedo feedback. The ice models of the SHEBA camp illustrate the interdependence of the dynamics and thermodynamics in the ice–albedo feedback and suggest that both must be represented appropriately in global climate models.

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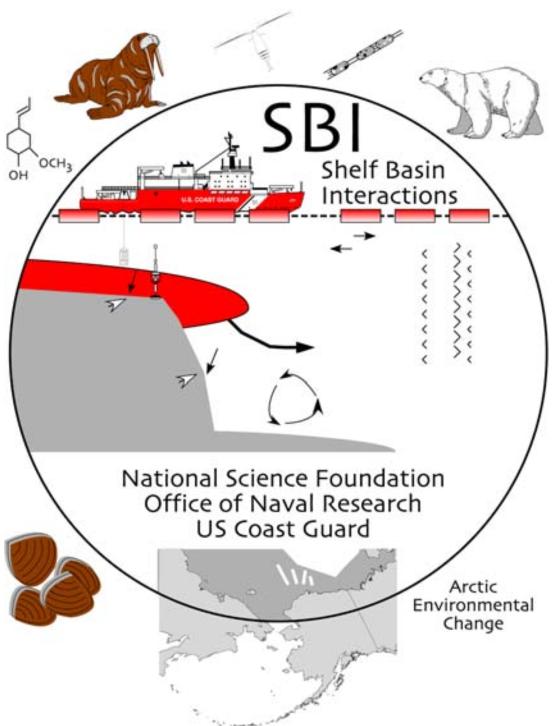
The Western Arctic Shelf–Basin Interactions Project

This article was prepared by Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Department of Ecology and Evolutionary Biology, The University of Tennessee, on behalf of all the SBI Phase II participants, who provided many of the concepts and results outlined in this article.

Further information on the overall SBI project can be found on the SBI web site (http://sbi.utk.edu) or by contacting Jackie Grebmeier, Director of the SBI Project Office and SBI Project Chief Scientist, Marine Biogeochemistry and Ecology Group, Department of Ecology and Evolutionary Biology, The University of Tennessee, 10515 Research Drive, Suite 100, Bldg A, Knoxville, TN 37932; phone: 865-974-2592; fax: 865-974-7896; email: jgrebmei@utk.edu.

The National Science Foundation and the Office of Naval Research are supporting an interdisciplinary global change research study known as the Western Arctic Shelf–Basin Interactions (SBI) project. This project is part of the Ocean–Atmosphere–Ice Interactions component of NSF's Arctic System Science program. The goal of the SBI project is to improve our ability to assess the impacts of global change on the physical and biogeochemical connections among the western Arctic shelves, slopes, and deep basins. The SBI project focuses on shelf, shelf break, and upper slope water mass and ecosystem modifications, material fluxes, and biogeochemical cycles. The geographical focus is on the Chukchi and Beaufort Seas and adjacent upper slopes. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the Arctic shelves and the adjacent ocean basins. SBI therefore focuses on the outer shelf, shelf break, and upper slope, where it is believed that key processes control water mass exchange and biogeochemical cycles and where the greatest responses to climate change are expected to occur.



The SBI project consists of three phases over a 10-year period. Phase I (1998–2001) involved analyses of historical data, opportunistic field investigations, and modeling of specific regions and processes. SBI Phase II constitutes the field program taking place in the Bering Strait region and over the outer shelf, shelf break, and slope of the Chukchi and Beaufort Seas into the Arctic Ocean. Phase III will focus on the development of pan-Arctic models suitable for simulating scenarios of the impacts of climate change on shelf–basin interactions.

The SBI field program has been developed to focus on:

- Physical modifications of North Pacific and other waters on the Chukchi shelf and slope, and exchanges of these waters across the shelf and slope;
- Biogeochemical modifications of North Pacific and other waters over the Chukchi and Beaufort shelf and slope areas, with an emphasis on carbon, nutrients, and key organisms that represent the suite of trophic levels; and
- Comparative studies over the wide Chukchi and narrow Beaufort shelves and adjacent slopes to facilitate extrapolation and integration of the Western Arctic work to a pan-Arctic perspective. Integrated process and modeling studies of shelf–basin exchange processes and their sensitivity to global change will be an important methodology in this extrapolation. A physical–biological coupled model is being undertaken as part of the SBI study.

Through integrated field and modeling efforts, the SBI project is investigating the effects of glo-

The USCGC Healy *anchored against an ice flow for SBI work.*

bal change on production, cycling, and shelf–slope exchange of biogenic matter, both seasonally and spatially. To this end, there are five study objectives deemed both timely and essential to improving our understanding of the effects of global change on productivity as it contributes to shelf–basin interactions within the Arctic Ocean ecosystem:

- Understanding the roles of physical processes in the transport and modification of water and biogenic materials across the shelf and into the interior basin;
- Identifying mesoscale oceanographic features that support locally elevated concentrations of benthic and pelagic biota;
- Quantifying upper ocean (water column and sea ice) primary productivity in relation to the biomass and diversity of benthic and pelagic primary and secondary consumers;
- Assessing the relative importance of top-down as compared to bottom-up controls over pelagic–benthic coupling, biotic complexity, and carbon partitioning among different trophic levels; and
- Assessing food web changes consequent to the impacts of changing ice cover and hydrographic parameters on remineralization of organic matter, recycling efficiency, and biogeochemical fluxes.

Further details on the SBI project can be found in the SBI Science Plan and the Implementation Plan.

The 2002 SBI Field Program

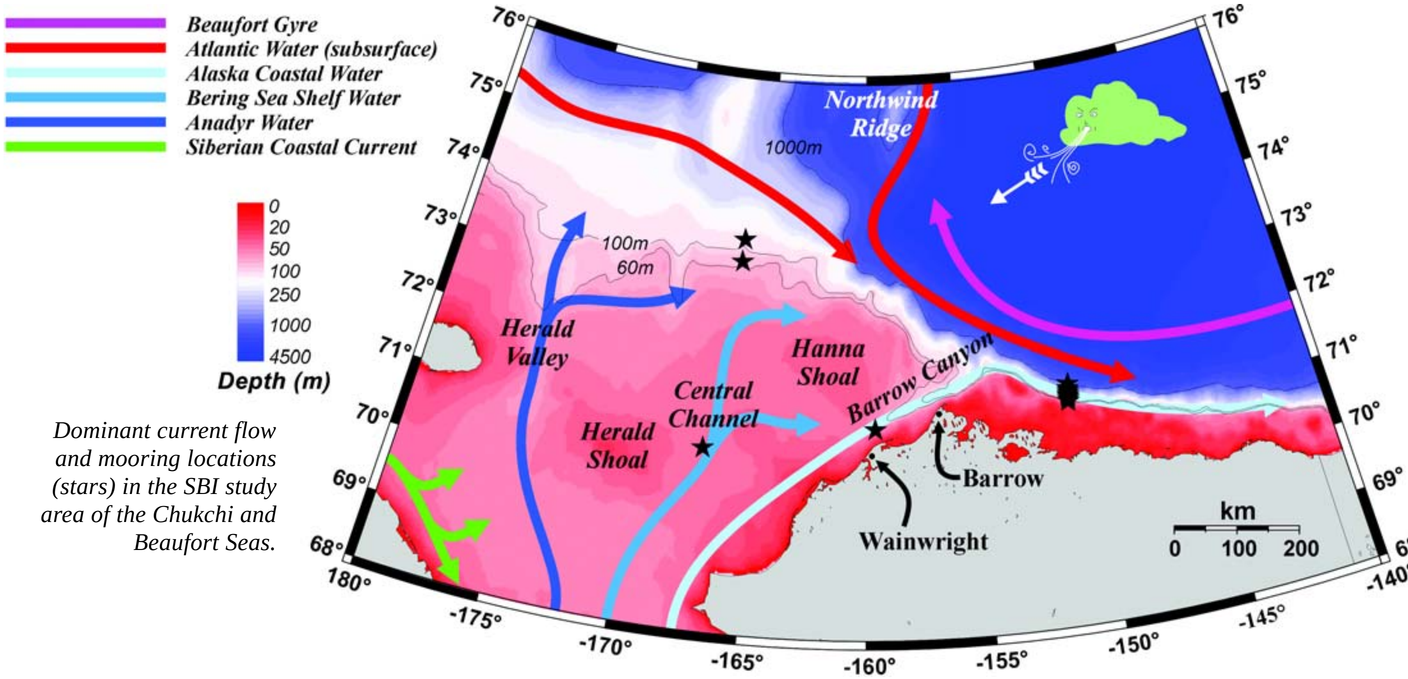
In 2002 the field phase of the SBI project included four successful scientific missions to the Arctic using three vessels: the USCGC *Healy* (5 May–15 June and 17 July–26 August), the USCGC *Polar Star* (15 July–13 August), and the RV *Alpha Helix* (20–29 June). Up to 39 scientists from 19 institutions in the U.S., Bermuda, Canada, and Europe participated in any one cruise, depending on the ship and its objectives. During the field program the SBI project applied a broad array of physical, biogeochemical, and biological measurements from May through September (and year-round with the moorings) that are almost unprecedented in scope for the Arctic. The spring cruise on the new *Healy* icebreaker was the first interdisciplinary research cruise to this region by a science vessel at this time of year.

SBI Hydrographic and Mooring Cruises

The current structure in the SBI study area includes three northward-flowing water masses passing through Bering Strait: Anadyr Water in the west, Alaska Coastal Water in the east, and Bering Sea Shelf Water occurring between these two water masses. These water masses move across the shelf to the north, then east as they meet the eastward-flowing slope boundary current at the interface with the Atlantic water and are carried eastward as well as offshore to the Arctic Basin.

The physical oceanographic and mooring component of SBI was undertaken during two cruises: one in June on the *Alpha Helix* and from mid-July to mid-August on the *Polar Star*. The primary aims of this component are to identify and understand the transport of water through Bering Strait and to understand the water masses and mechanisms by which shelf waters ventilate the western Arctic halocline. The major goals of the SBI June cruise were to emplace three mooring arrays in Bering Strait to capture the inflow characteristics of water transiting both the eastern and western channels of Bering Strait. The SBI summer 2002 goals were to deploy a system of moorings that will measure the outflow from the Chukchi shelf; to deploy a high-resolution moored array across the Beaufort slope, downstream of the outflows, to determine how these waters are fluxed into the interior; and to conduct a hydrographic survey encompassing locations along the Chukchi and Beaufort shelf edge.

The moored instruments will measure currents, temperature, and salinity numerous times per day until September 2003 (when they will be turned around for a second year-long deployment). A combination of discrete sensors and profiling instruments are being used. In addition, some mooring arrays in Bering Strait and the Central Chukchi Channel are outfitted with a fluorometer, a nitrate analyzer, and a turbidity meter. Nearly all



Dominant current flow and mooring locations (stars) in the SBI study area of the Chukchi and Beaufort Seas.

hydrostations during the cruise included water sample measurements of salinity and nutrients. The conductivity/temperature/depth package was also outfitted with a turbidity sensor, a fluorometer, and a lowered acoustic doppler current profiler measuring absolute horizontal velocity. These additional sensors provided invaluable information on the origin and magnitude of the currents in the region. Finally, the Beaufort Sea array consisted of eight moorings spaced 5 km apart, with an additional whale-listening mooring deployed by the National Marine Mammal Laboratory.

Hydrographic surveys completed during the mooring cruise represented the first systematic coverage of the three outflow branches of the Chukchi Sea: Herald Valley, the Central Channel, and Barrow Canyon. Additionally, sections were occupied downstream of both the Herald Valley and Barrow Canyon outflows, and the cruise included the first high-resolution crossings of the shelf and upper slope in this area of the western Arctic. Preliminary data on the origin and fate of the shelf-edge boundary currents indicate that the outer shelf of the Herald Valley outflow site is filled with cold, dense, Pacific-origin winter water as it flows eastward, forming a shelfbreak jet. The bottom water in this region has high turbidity, likely due to sediments drawn into this water mass as it crosses the shelf. Small lenses of water observed at the shelf edge are likely the beginnings of eddies. At the eastern end of the domain in the Beaufort Sea, a transect revealed the presence of a fully developed subsurface anti-cyclonic eddy comprising cold, turbid, Pacific-origin winter water. This is the same type of eddy that has been observed repeatedly throughout the interior of the Canada Basin, a result that suggests that these eddies emanate from the shelf-edge boundary current.

SBI Process Cruises

Thirty to fifty stations were occupied each cruise over five transect lines: one line over the shelf and slope of Herald Valley in the Chukchi Sea, two shelf-to-basin lines from the Chukchi outer shelf to the Arctic Basin (one west of Hanna Shoal and one east of Hanna Shoal), a transect down Barrow Canyon, and a shelf-to-basin line east of Barrow. Additional stations were also occupied near the Alaska coastline.

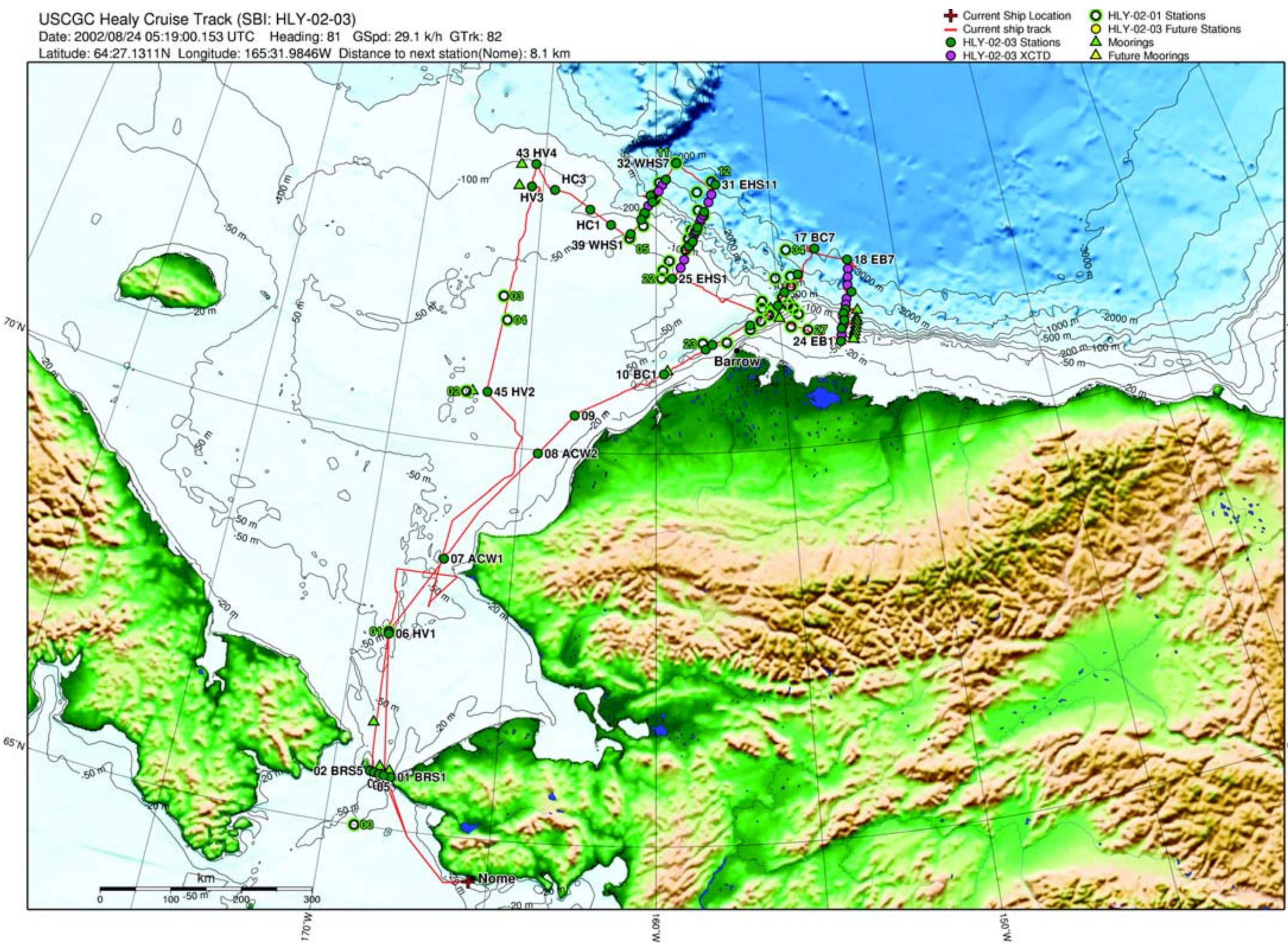
During the spring process cruise, ice observations were carried out from the ship's bridge at two-hour intervals when the ship was underway and once at every station along the entire cruise transect. Observations included prevailing ice types, ice thickness, snow depth, and distribution of open water, as well as estimates of ice colonized by ice algae ("brown ice") and containing sediment entrained during ice growth ("dirty ice"). Towards the north, both sediment-laden ice and bottom communities exhibited a distinct (though not quite coincident) boundary with clean ice northwards of roughly 73°40'N (on the west Hanna Shoal line). The northernmost stations of the

Cruise reports for both process and mooring cruises are available on the SBI web site (http://sbi.utk.edu).

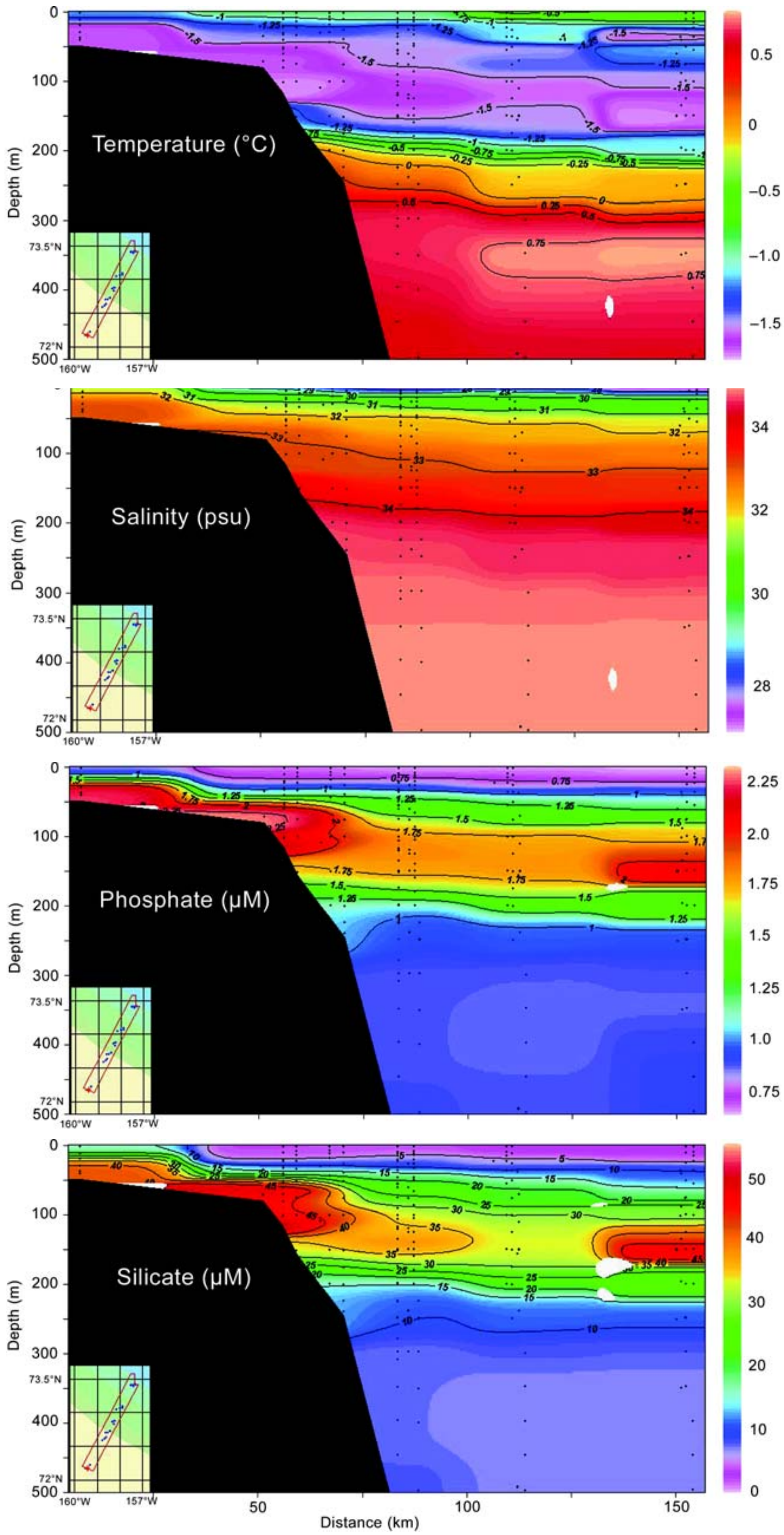
west and east Hanna Shoal transects were located in predominantly second- or multi-year ice, corresponding well with information on last summer's minimum pack ice extent obtained from satellite data.

Hydrographic collections were made during both the spring and summer process cruises using a conductivity/temperature/depth (CTD) and bottle rosette. Bottle samples were analyzed for salinity, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, dissolved silicon, urea, and chlorophyll. Surface salinities of less than 30 psu were recorded as the ship moved eastward and offshore into the Beaufort Sea, presumably because of a general freshening of the surface waters as the ship departed the region under the direct influence of the Bering Strait inflow and because of the accumulated effects of icemelt and river runoff. Temperature and salinity vs. depth profiles in Barrow Canyon varied more from station to station than they did in the sections outside of the canyon, indicative of the dynamic nature of the offshore and onshore current flow within this canyon. In addition, the western Chukchi Sea showed two regions of increased southeastward flow near the shelf edge: one right at the shelf break transporting shelf-origin water and one a bit offshore and deep transporting warm Atlantic water. An eddy-like feature was found centered near a depth of 100–150 m on the east Hanna Shoal line, with a warm center and cold water on either side of it, indicating a strong shoaling of Atlantic water properties onshore. Understanding these features will aid in investigating how physical and biochemical products are transported from the shelf to the basin.

The nutrient regime measured on three transects during the spring cruise indicated high initial nutrient concentrations over the shelf near Bering Strait, decreasing eastward and seaward. Although high nitrate levels are characteristic of the study region in spring, conditions encountered



Detailed USCGC Healy *cruise track plot from the SBI 2002 process cruises. The locations of moorings and past, present, and future measurement stations are shown. The map background is a combination of USGS elevation data and bathymetry data from the International Bathymetric Chart of the Arctic Ocean.*

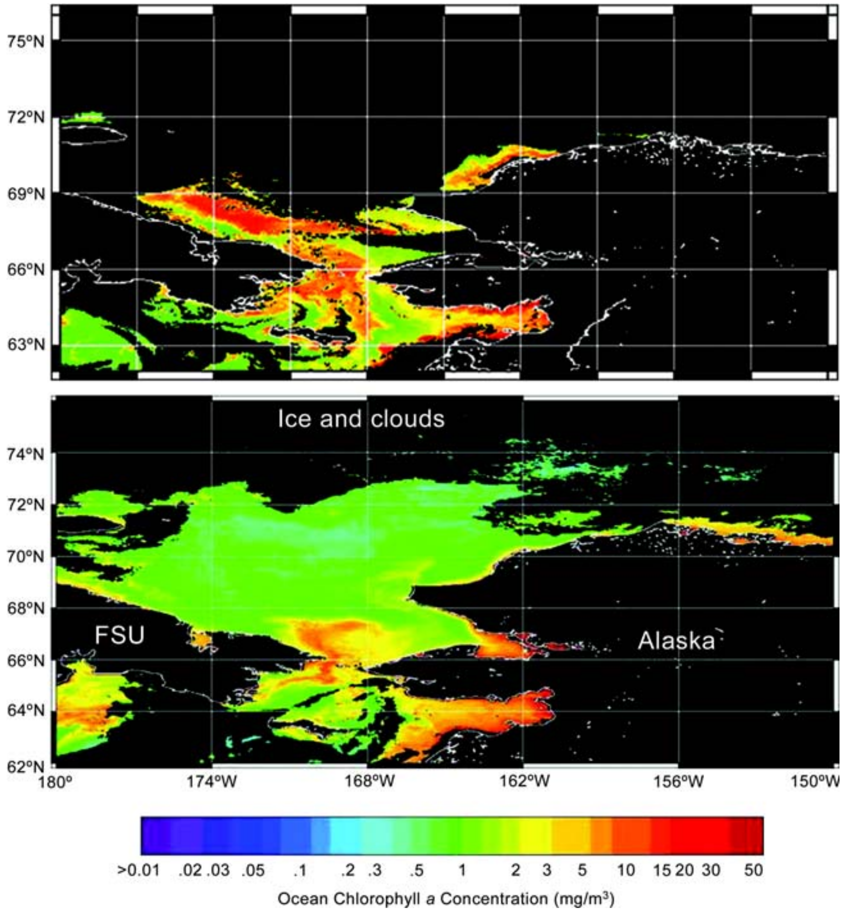


Vertical distribution of key variables on the East Hanna Shoal line during the summer of 2002.

during this period suggested the initiation of an inshore phytoplankton bloom on the Barrow Canyon line. While a strong decrease in nutrients was expected as the ship departed the region under the direct influence of the Bering Strait inflow, the lack of nitrate in surface waters at the offshore stations was somewhat surprising since this was early in the "growing" season. Preliminary observations indicate that the spring bloom may have already occurred, at least in the surface layer, at the offshore sites. Observations and comments on productivity in this region are scarce, so it is uncertain whether this early blooming is "normal" or related to the recent warming of the Arctic. As the ship entered deep water, the expected nutrient maximum was found at about 125 m associated with Bering Strait/Chukchi waters that form the upper halocline. Nutrient concentrations in this maximum appear to be a bit lower than in the past, but determining whether this is correlated with the recent warming and freshening of the Bering Strait inflow or is simply a normal space- or time-related difference between our data and past experiments will require further analysis.

During the summer SBI process cruise, all transects could be sampled because of the low ice cover in the study region for this time of year. Primary production was either occurring or at the end of its bloom period. In contrast with the spring SBI cruise, when several stations had surface nitrate concentrations in excess of 10 micromolar (pre-bloom conditions), surface nutrient concentrations were low during the summer cruise, with the highest water column chlorophyll near the bottom, suggesting post-bloom conditions. Microscopic analyses of phytoplankton supported these post-bloom conditions throughout the study region during the summer cruise.

Additional subsamples from multiple CTD and rosette casts were used to measure primary production, particulate carbon, inorganic carbon, biomarkers, microzooplankton, and radioisotope content. Shipboard sensors and measurements indicated that the colored dissolved organic matter (cDOM) had its maximum at 140–160 m on the slope and in the Canada Basin, just below the upper halocline maintained by Bering Strait inflow water. In addition, cDOM and physical oceanographic data support the occurrence of an eddy along the Chukchi slope on the east Hanna Shoal line. Anomalous concentrations of radium-224 (a signature of shelf products) and total dissolved nitrogen were measured in the core of the eddy feature. These observations were augmented



Satellite coverage of chlorophyll a in the SBI study area during June 2002 (top) and August (bottom) 2002.

by expendable CTD deployments and close-spaced CTD profiling undertaken along the east Hanna Shoal line. Eddies are one proposed mechanism for shelf–basin exchange.

In the spring, numerous clear days with good satellite coverage in the southwestern margins of the study area were sufficiently ice- and cloud-free for extensive ocean color observations from space. Primary production experiments and satellite data indicated that blooms occurred north of Bering Strait and to a lesser degree along the northwestern Alaskan coast and in areas of ice retreat. Of particular note were the large concentrations of ice algae in the water column at the shallow water stations in the spring. Shipboard measurements will assist in calibrating remote satellite observations seasonally over the study region and will enhance the annual coverage of the SBI study region.

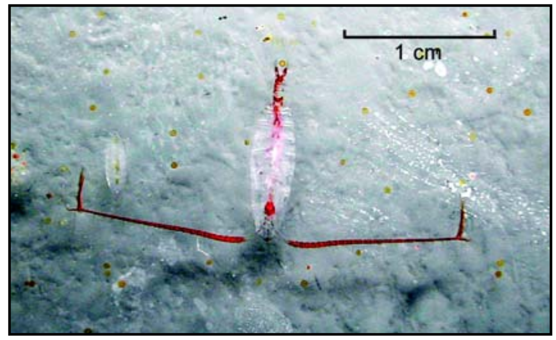
Water column particulate organic matter was greatest at the 50-m shelf stations, became reduced at the 100-m stations, and was negligible at deeper stations. An exception was Barrow Canyon, where extraordinarily cloudy water was collected at the 100- and 200-m stations because of high plankton productivity in the water.

In-situ pumps were also used to measure the activities of the naturally occurring, particle-reactive radionuclide thorium-234 to trace particulate carbon in combination with its parent, uranium-238, which is soluble in seawater. Particle export is enhanced in the shelf–slope region compared to the deep interior stations. There appears to be a subsurface scavenging signature near the shelf sediments that extends into the deep water, an indication of shelf–basin interactions.

Bacterial abundance was determined using a shipboard epifluorescence microscope. Preliminary results indicated roughly 50% lower counts than found in low-latitude oceanic waters. Both bacteria and bacterivorous flagellates were common in the upper water column, whereas there were many occurrences of a deeper chlorophyll maximum layer of large diatoms. The accumulation and decay of diatoms suggests that plankton grazers are not able to consume most of the spring bloom and that instead the bulk of the bloom is decomposed by heterotrophic microbes or sinks to the benthos. Coincident measurements of microzooplankton grazing rates also indicated very low metabolic rates during this spring, ice-covered season. Bacterial abundance was highest in the surface waters, where the amount was twice as high in the summer as in the spring. Bacterial production was ten times higher in the summer than in the spring.

Various nets were used to collect size fractions of micro-, macro-, and mesozooplankton for both population and experimental purposes. Plankton nets were often clogged by chain-forming diatoms in the spring at the shallow stations. At the deeper stations, phytoplankton abundance was much reduced, and different species of both chain-forming and centric diatoms were most important. For mesozooplankton, Pacific water copepod and euphausid species were observed in the Chukchi shelf stations, indicative of the water type they transited in. In general, Pacific-type copepods were the most important shelf species, whereas Arctic- and Atlantic-type copepods were more important in deeper waters.

In addition to standard net collections, a special zooplankton sensor was used on the cruise for video recording of plankton in the water. Preliminary analysis of the digital files suggests a higher density of plankton on the shelf, which, according to shipboard grazing and egg production measurements, was likely caused by the occurrence of the phytoplankton bloom and high feeding and egg production of key copepod species.



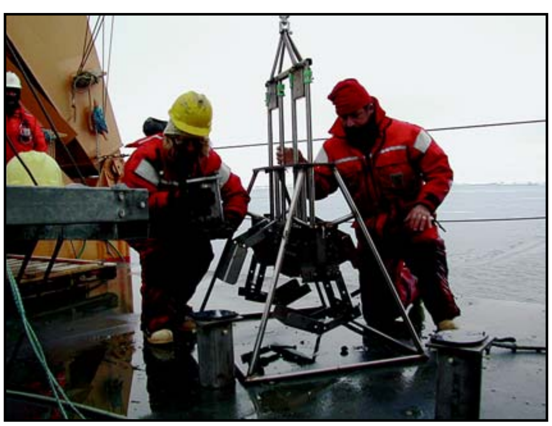
Using a vertical net for collecting zooplankton (near right) and a calanoid copepod with red antennae and yellow eggs (far right).

Benthic grabs and cores were used to collect benthic fauna and sediment samples for population, community structure, food web, chemistry, and metabolism studies. A variety of sediment processes indicate patterns of sediment focusing and recycling in the SBI study region. Sediments collected with benthic coring devices indicated that sediment oxygen uptake and nutrient flux (an indication of carbon supply), along with denitrification, occur on the shelves. A regular pattern of high to low rates was observed from the shelf to the deep basin. Both radioisotope and sediment tracer studies indicate that phytodetritus is rapidly deposited to depths as great as 1000 m along the Barrow Canyon and East Barrow transect lines since the time of the spring cruise. It is notable that higher sediment uptake rates occurred at deeper depths in Barrow Canyon than along the other transect lines, probably because of a focusing of organic carbon down the axis of the canyon.

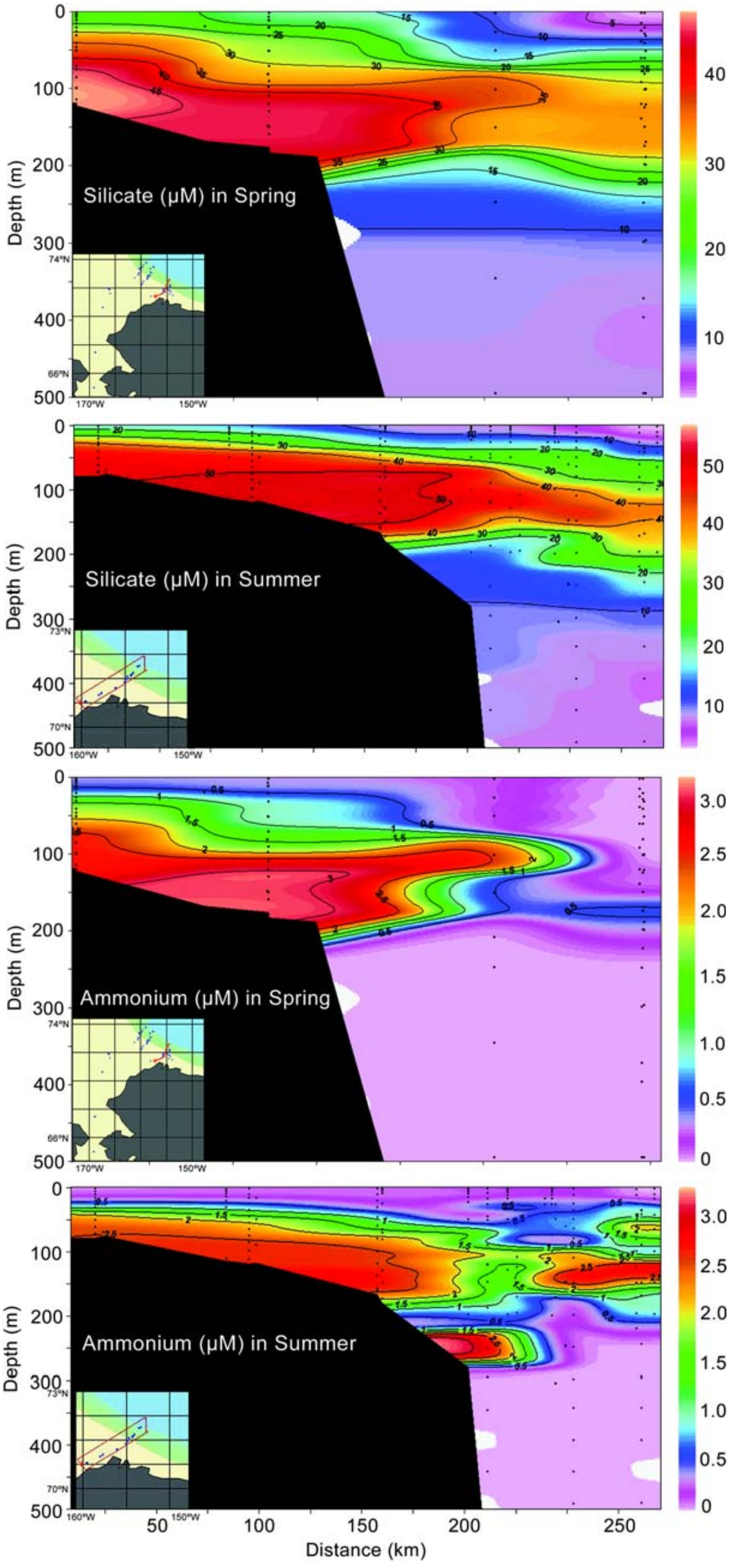
Benthic macrofaunal populations also follow the trend in carbon deposition to the benthos. Shelf water column plankton samples also contained large numbers of young forms of bottom-dwelling invertebrates (such as marine worms, crabs, clams, and tunicates) coincident with high phytoplankton, indicating that this region acted as a nursery for various benthic species that release their larval stages into the water column at this time of year. Benthic biomass and diversity were greatest at the 50- to 100-m stations, declining down to 500 m deep, and negligible at water depths of 1000 m and greater. The species collected from the greater depths were small and limited to foraminifera, clams, and marine worms. The Barrow Canyon stations had well-sorted cobbles and gravel and a greater number of filter-feeding animals than at other stations.

Shallow oxygen penetration in sediments in Barrow Canyon sections also suggests sediment focusing and off-shelf carbon transport in the Barrow Canyon area. In contrast, the East Hanna shoal section to the east of Barrow Canyon had deep oxygen penetration, likely a reflection of low relative productivity and consequently low carbon rain rate to the sediments.

Modification of waters over the shelf and transport of biogenic signals from the shelf to the



Sediment sampling using a HAPS benthic corer (near right) and the resultant sediment core with animals from Barrow Canyon (far right).



Nutrient concentrations along the Barrow Canyon line for silicate and ammonium in spring and summer measured during the SBI field project in 2002.

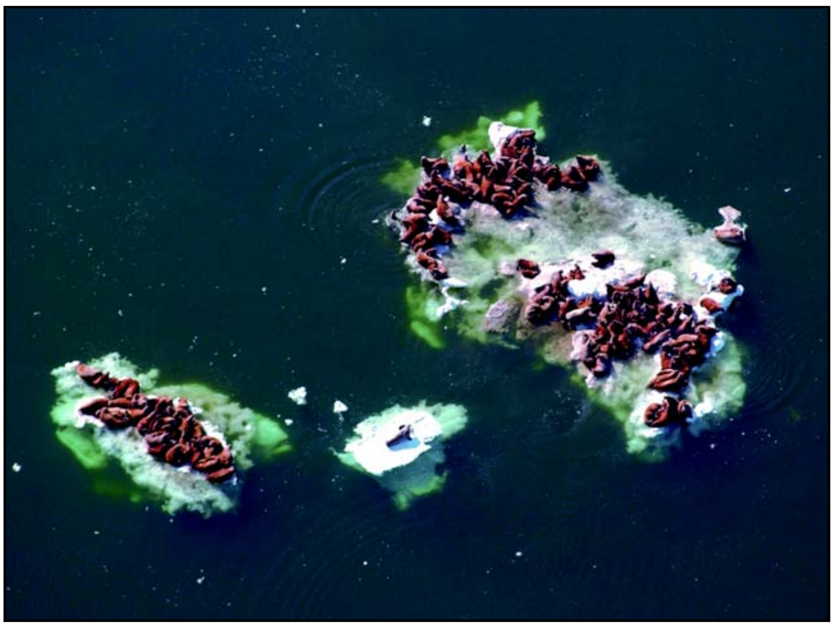
basin were observed during all cross-shelf sections for every SBI cruise on the main transects (see the figure to the left). It is notable that when comparing spring vs. summer data from the same hydrographic sections, we see an increase of 5–10 micromolar in maximum silicate concentrations in the plume originating over the shelf in Barrow Canyon, as well as pulses of ammonium moving off the shelf to the deep basin. This observation suggests fairly rapid settling and remineralization of diatoms produced by the spring bloom over the shelf. By the time of the summer SBI process cruise, most of the production had settled downwards in the water column and undergone transformation in the water and sediments. Maxima in other variables had a tendency to peak offshore and to intersect the shelf break instead of the shallower portions of the shelf.

Marine mammal studies by the U.S. Fish and Wildlife Service during the 2002 SBI spring cruise recorded 291 sightings of seven species of marine mammals, with the following distribution by species and number of sightings (in parentheses): walrus (78), bearded seal (29), ringed seal (29), spotted seal (10), unidentified seals (96), polar bear (19), bowhead whale (6), gray whale (14), and unidentified whales (10). The 19 sightings of polar bears including five of mothers with one or two cubs. In mid-June two helicopter flights produced sightings of over 50 groups of walruses, and high-resolution vertical digital photographs were obtained from approximately 45 of these groups. Group size, area covered by groups, and group composition will be determined from the photographs and used to develop correction factors for future surveys using remote sensing systems.

SBI Data Support and Outreach Activities

In support of the SBI field program, the Joint Office of Science Support (JOSS) group maintained a shipboard field catalog during both process cruises on the *Healy* that provided real-time data to scientists on the ship. Some data were also made available to onshore PIs who were following the progress of the cruise. Field products included satellite images, ship tracking, weather, CTD data from the hydrographic group as well as associated bottle data, and shipboard event logs. The SBI field catalog (with maps and event information at sea) can be found on the JOSS web page (http://www.joss.ucar.edu/sbi/catalog/).

In addition to the research information available through the JOSS and SBI web sites, public outreach was provided to explain our research program during the summer cruises. A broadcast crew from *CBS News* and reporters from *USA Today* and the Associated Press were aboard the *Healy* during the summer cruise transit of Barrow Canyon. Interviews were also provided to a reporter for the *Nome Nugget* before the *Healy* left port and to KBRW-AM/FM, a National Public Radio affiliate in Barrow that broadcasts across the North Slope Borough, during the cruise using the Inmarsat telephone capabilities. An article was released by the Associated Press wire and appeared in a number of newspapers, including the *Baltimore Sun*, *Orlando Sentinel*, *Fresno Bee*, and *Juneau Empire*. *CBS News* broadcast three stories on August 28, 29, and 31, 2002, on their national evening news program, and another piece was presented on the *CBS News Sunday Morning* program in January 2003. The repeat visits of the *Healy* to Nome this past summer were covered by the *Nome Nugget*, particularly in their issues of June 20 and August 29, 2002. Some of the media coverage is presented on the SBI project web site (http://sbi.utk.edu) as well as coverage of the mooring cruise operations (http://www.whoi.edu/arcticedge).



A herd of walruses observed in the SBI study area in the spring of 2002.

A valuable addition to the SBI research program was the participation during the summer SBI process cruise of Betty Carvellas, a Vermont high school teacher who provided daily updates on research and ship operations, including spotlights on individual research groups, explained in layperson's terms. These daily updates are accessible through the Teachers Experiencing Antarctica and the Arctic web site (http://tea.rice.edu, specifically http://tea.rice.edu/tea_carvellasfrontpage.html). While aboard the cruise, she also served as a team member with the group investigating water and sediment tracers, sediment metabolism, and benthic community structure. Outreach activities during the cruise included a tour of the *Healy* for students from the Anvil City Science Academy (a public magnet school in Nome) while the ship was anchored off Nome. Also during the cruise she made Inmarsat-telephone-aided Powerpoint presentations of cruise activities to a district-wide teachers in-service at Essex (Vermont) High School and to a public forum in Colchester, Vermont.

Future SBI Field Program

Plans for the 2003 SBI field season include a March helicopter survey and field sampling project, participation by some SBI PIs in an April ice camp sponsored by the Office of Naval Research, the annual June Bering Strait mooring project, a June–July hydrographic and sampling survey cruise to the Chukchi and Beaufort Seas, and a September–October mooring turnaround cruise to retrieve and redeploy both the Chukchi and Beaufort Sea mooring arrays. The 2004 field season will proceed with four cruises similar to those undertaken in 2002 to provide an interannual comparison of processes in the SBI sampling region. Phase II of SBI will continue through 2006 with data synthesis. The final Phase III of the SBI project (2007–2009) will focus on developing pan-Arctic models suitable for simulating scenarios of the impacts of climate change on shelf–basin interactions.

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The Russian–American Initiative for Land–Shelf Environments in the Arctic

Contributions to Arctic System Science

This article was prepared by Lee W. Cooper, Department of Ecology and Evolutionary Biology, University of Tennessee, with assistance from RAISE principal investigators.

The Russian–American Initiative for Land–Shelf Environments (RAISE) is unique among research program and project components supported by the National Science Foundation's (NSF) Arctic System Science Program (ARCSS). RAISE project implementation has been explicitly international, and the program is the only cooperative, bilateral research program supported by both NSF and its Russian counterpart agency, the Russian Foundation for Basic Research (RFBR).

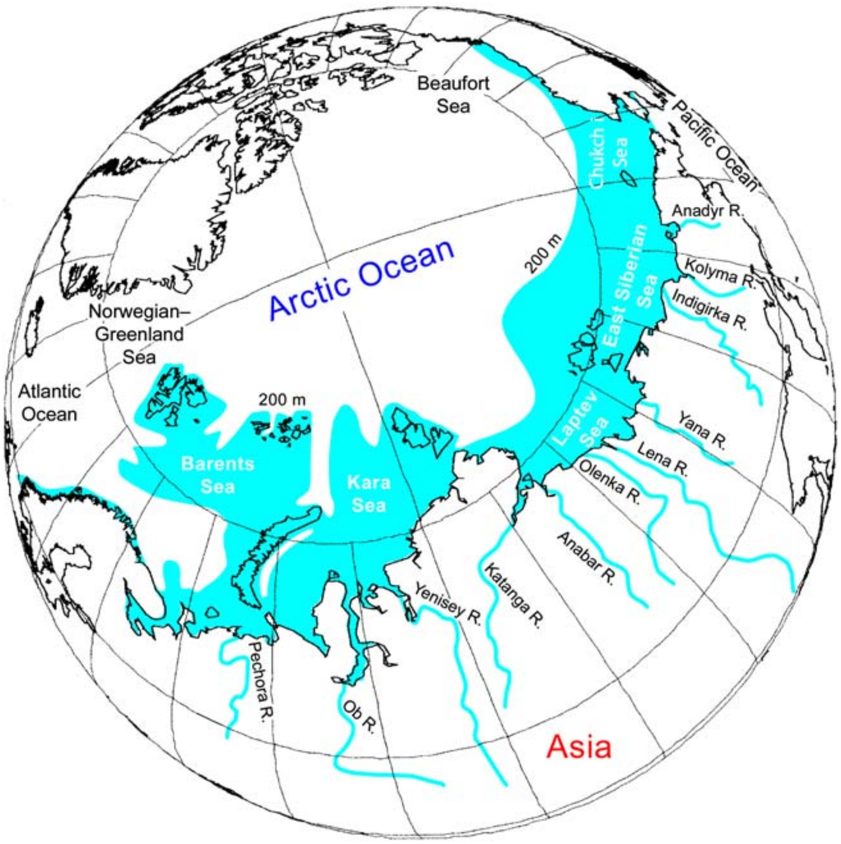
The goal of RAISE is to facilitate bilateral (U.S.–Russian) research at the land–sea margin in the Eurasian Arctic, focusing on the scientific challenges of environmental change in human and biological communities and related physical and chemical systems. The RAISE program has historically been one of the key ARCSS mechanisms for supporting global change research beyond the relatively small portion of the Arctic shared by the United States. A more general objective of RAISE specifically has been to facilitate cooperation between Russian and U.S. scientists that would improve knowledge of Arctic system science on both land and sea in the large portion of the Arctic that is in the Russian Federation.

The scientific justifications and bases for the RAISE umbrella of research priorities were identified by participants in three international workshops held in Columbus, Ohio; St. Petersburg, Russia; and Arlington, Virginia in 1995 and in annual follow-up meetings of RAISE investigators and the RAISE International Science Steering Committee over the past eight years. The results of these scientific deliberations are available from the RAISE web site (http://arctic.bio.utk.edu/RAISE/index.html) or from the RAISE project office at the Department of Ecology and Evolutionary Biology at the University of Tennessee.

Since the publication of the RAISE prospectus that resulted from these science planning efforts, a number of land- and sea-based, remotely sensed, or archived data recovery research projects involving both U.S. and Russian scientists have been initiated. Summaries of many of these projects, both Russian and U.S. based, are also available at http://arctic.bio.utk.edu/#raise, and a summary in written form has also been recently published.

Despite this progress, the scale of research supported through RAISE has been limited by the complexities of undertaking bilateral research in the Russian Federation. Changing political realities in both the United States and Russia, economic dislocations that have affected the abilities of Russian scientists to pursue their vocations, logistical challenges in the Russian Arctic, and the lack of high-level governmental agreements between the Russian and U.S. governments that would facilitate bilateral research have resulted in RAISE projects that are largely scientist-to-scientist in implementation. Although this orientation towards supporting individual projects has been effective, there have also been no large-scale multi-investigator projects such as Surface Heat Budget of the Arctic (SHEBA) and Shelf–Basin Interactions (SBI) that have been coordinated through the Ocean–Ice–Atmosphere Interactions (OAII) Management Office of ARCSS.

The lack of coordinated projects within RAISE may be ending. Many projects recently funded through the Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) are utilizing research priorities identified in the RAISE prospectus and involve coordinated teams of Russian and U.S. investigators studying runoff impacts from Eurasian rivers on the climate-linked thermohaline processes in the world ocean. Also, science planning is underway for a coordinated Land–Shelf Interactions (LSI) initiative that has a goal of providing a coordinated, interdisciplinary research opportunity in the Arctic that would focus on the coastal zone and would support land-, river-, and sea-based researchers who would take advantage of coordi-



nated logistical capabilities that would otherwise be unavailable. This new research initiative also has a goal of transcending the traditional geomorphic boundaries separating marine and terrestrial lines of inquiry in Arctic system science. Development of the initiative and identification of key research priorities are being coordinated by the RAISE/LSI Project Office at the University of Tennessee.

Despite the relatively modest financial investment in the RAISE effort, the initiative has been effective in coordinating bilateral U.S.–Russian research of importance to understanding and predicting the impacts of global change in the Arctic. In the following discussion, research highlights from selected RAISE projects are outlined, with time scales of interest in the past and present, as well as predictive modeling for future environmental change.

RAISE Research Highlights

Paleoclimate

One of the key aspects for understanding the global environment impacts of environmental change in the Arctic is the scope and scale of these changes in the past. Within the past decade, RAISE researchers have contributed several key insights to our understanding of past Arctic climate and its relationship to biogeochemical processes at high latitudes and the processes that link with the world climate system.

One uncertainty in interglacial paleoclimatic reconstruction is the extent to which ice sheets were present at the time of the Last Glacial Maximum (LGM) in northeastern Siberia and their extent in general in the Northern Hemisphere. The presence or absence of such ice sheets geographically is important for validating atmospheric global circulation models during both glacial and interglacial periods, which depend on accurate sea-level reconstructions and accurate estimates of glacial ice volume. Knowledge of the extent of glacial ice is also important for evaluating global ice balance and the mechanisms for transitions between glacial and interglacial periods. RAISE-related research efforts in particular have been important for defining the limits of glaciation over a wide geographical region of the Russian Arctic.

Inferences for significant glacial ice volumes in the Wrangel Island and East Siberian Sea region at the time of the last glacial maximum have been directly tested during field studies by RAISE investigators on Wrangel Island. Studies using the cosmogenic radionuclides ^{10}Be and ^{26}Al, which provide a time history of atmospheric exposure, and field studies on the island that have documented the paucity of glacial geomorphological features (such as landforms, moraines, and glacial erratics) have led the RAISE investigators to conclude that Wrangel Island remained free of extensive glacial ice during the LGM. The lack of moisture caused by the continental climate on the emergent Bering Land Bridge is the most likely reason for limited ice in this part of the Arctic during the LGM.

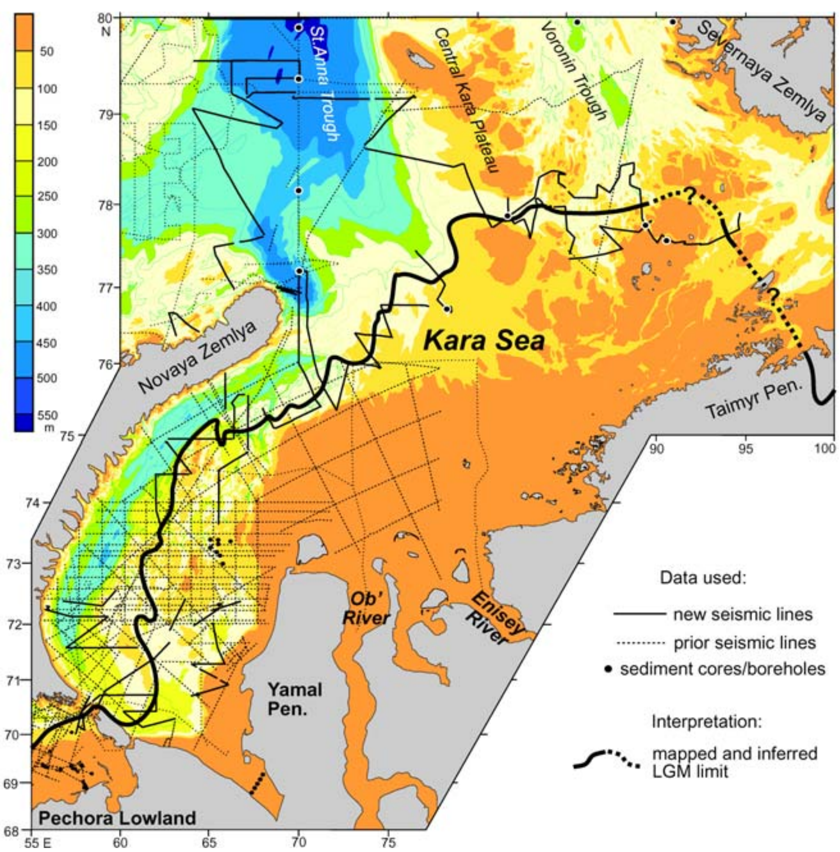
Additional work on this project is documenting Pleistocene marine transgressions on Wrangel Island. The Tundrovayan Transgression (459,000–780,000 years ago) is represented by raised marine deposits and landforms that are 15–41 m above the current sea level and up to 18 km inland. Evidence of a high sea level between 64,000 and 73,000 years ago is preserved in deposits and landforms 4–7 m above the current sea level in the Krasny Flag valley on Wrangel Island. These deposits and landforms were mapped, dated, and described using amino acid geochronology, radiocarbon, optically stimulated luminescence, electron spin resonance, oxygen isotopes, micropaleontology, paleomagnetism, and soil grain sizes. The marine deposits reflect past sea levels and have not been uplifted. The presence of marine deposits that predate the LGM also indicates that neither Wrangel Island nor the East Siberian or Chukchi Seas experienced extensive glaciation over the last 64,000 years.

In a parallel RAISE-supported effort, the extent of Arctic ice sheets during the LGM is also being studied in the Kara and Barents Sea region using sediment coring and seismic profiling. The extent of glaciation here is an issue of intense debate, involving a question of whether the West Siberian rivers have been blocked by glaciers from discharging into the Arctic Ocean. Characterization of subbottom sediment structure and stratigraphy is providing initial supporting evidence that major Siberian river runoff was blocked or dammed on the Kara Sea shelf at the time of the LGM, followed by a rapid inundation of the continental shelf. Both of these events can be expected to have had a significant impact on climate. Glaciation limits and Holocene peat accumulation has also been studied on the Yamal Pensinula.

A separate, more recently funded project is investigating the glacial history of the Severnaya Zemlya Archipelago during the LGM and earlier glacial periods. This project closely complements the marine efforts in the adjacent Kara Sea, discussed above, and will help constrain the extent, volume, and timing of ice sheets in the northern Kara Sea and adjacent land areas. Preliminary stratigraphic and geomorphic data from a first field season on Severnaya Zemlya in the summer of 2002 provide evidence for three Late Quaternary glaciations on southern October Revolution Island. Significant isostatic depression associated with at least two of these glaciations caused subsequent deposition of marine sediments and the formation of raised beaches at altitudes up to approximately 130 m above current sea level, suggesting regional glaciation, not just expansion of local glaciers. Ice directional indicators (glaciotectonic structures, clast fabrics, and striations) associated with these two glaciations show southerly flow into the Kara Sea. Numerous samples were collected to constrain the age of the glaciation events, the oldest of which may predate the Last Interglacial (more than 130,000 years ago). As had been reported by prior investigators, the LGM glaciation is poorly expressed and may not have expanded much beyond the present ice limits. A second field season in 2003 is planned to better define the LGM limits, adding to the many RAISE-related research efforts that are delimiting glaciation over a wide geographical region of the Russian Arctic.

Following de-glaciation at the start of the Holocene, large amounts of carbon were synthesized and remain stored as peat in the West Siberian lowlands (WSL) in the Ob' and Yenisey River basins. U.S. and Russian investigators have been working together to reconstruct the history of this carbon sequestration using radiocarbon dating as well as geographic information systems and remote sensing tools. The WSL is the world's highest-latitude wetland, covering nearly two thirds of West Siberia. The carbon sequestered in the WSL has been conservatively estimated at more than 10% of the global carbon pool stored in soils. Much of this peat accumulation initiated over a wide range of latitudes and geographical area approximately 8,000–10,000 years ago. This timing of peat accumulation is consistent with studies on the Yamal Peninsula, where a prominent birch horizon is also present below peat that is approximately 9,000 to 10,000 years old. This vegetation change is consistent with a northward shift of the treeline of more than 200 km from the present limits, corresponding to a 2–4°C summer

Map of the Kara Sea with reconstruction of the probable LGM ice sheet limit. Bathymetry is from navigational charts detailed using seismic reflection data.



warming across northern Eurasia. Improved estimates of the WSL carbon pool and documentation of changes in drainage and carbon sequestration patterns are additional expected outcomes of this RAISE research project.

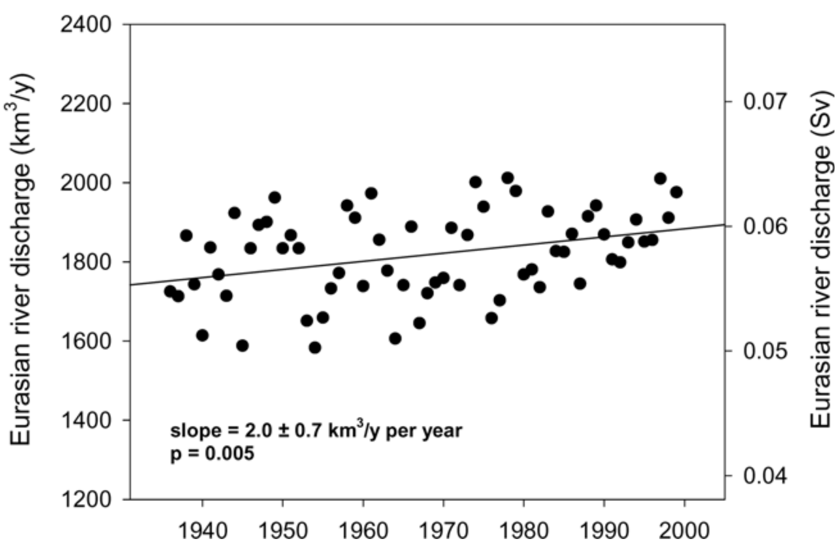
Contemporary and Historical Processes

Historical hydrographic records collected during the Soviet era are also being used in syntheses of runoff data. Recently reported results indicate that the average annual discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean increased by 7% from 1936 to 1999. The average annual rate of increase has been 2.0 ± 0.7 cubic kilometers per year. As a result the average annual discharge volume from these six rivers is currently about 128 cubic kilometers per year greater than it was when discharge monitoring began in the 1930s. This RAISE project has also correlated annual discharges with changes in the North Atlantic Oscillation and increases in global mean surface air temperatures. The observed large-scale change in freshwater influxes to the Arctic could ultimately have important implications for ocean circulation and climate. If the warming trend and correlated increase in runoff continue, the higher runoff fluxes into the North Atlantic and Arctic Oceans could affect ocean circulation and northern climate by reducing North Atlantic deep-water ventilation.

Related RAISE-supported research is evaluating historical runoff data quality, and more detailed studies are determining the highly variable nutrient fluxes associated with Arctic rivers, which in turn impact marine productivity. Fluvial sediment flux data from many of these rivers are also being synthesized to establish more accurate estimates of sediment fluxes. This is fundamentally important for understanding land–ocean linkages in the Arctic.

Another RAISE-related research project that is being supported jointly by the RFBR and NSF is contributing additional linked insights on interannual seasonal variability of Russian river discharge over the past 50 years. In this case, NSF support is being provided indirectly through its grant that supports the International Arctic Research Center (IARC) at the University of Alaska Fairbanks. In this research project, which includes investigators from the Pacific Oceanological Institute in Vladivostok, historical records have been used to document a significant positive trend for winter discharge from the three largest Siberian rivers over the past several decades. In the last three decades the mean winter discharge (November–April) has increased by 13% for the Ob', 45% for the Yenisey, and 25% for the Lena Rivers compared with prior periods. The total annual Siberian runoff into the Arctic has increased only 4.5% since the early 1970s, so this finding indicates a partial redistribution of runoff from summer to winter since the end of the 1960s. This change in the seasonal patterns of Siberian rivers discharge may be related to a periodic atmospheric climatic shift observed in the early 1970s over northeastern Asia as air and soil temperatures increased during winter.

Another topic of importance identified within the RAISE prospectus is coastal erosion. It has become evident that coastal erosion in some Arctic marginal seas is at least as important a source of sediment fluxes as is river runoff. This topic is also being addressed by RAISE research projects through both coordinated and individual efforts. The Arctic Coastal Dynamics (ACD) program (http://www.awi-potsdam.de/www-pot/geo/acd.html) is an international, coordinated effort, supported in part and sanctioned through the International Arctic Science Committee (http://www.iasc.no), that provides a multidisciplinary, multinational forum for exchanging and synthesizing ideas, data, and information related to erosion and sediment transport. The ACD was recently designated as a regional project of the International Geosphere–Biosphere Programme's Land–Ocean Interactions in the Coastal Zone project. Many of the project elements were formulated at the NSF-funded RAISE workshop in Woods Hole



Combined annual discharge from the six largest Eurasian Arctic rivers for 1936 to 1999. [Reprinted with permission from Peterson et al. (2002) Science, *vol. 298, p. 2171, which gives details about the data sources. © 2002 American Association for the Advancement of Science.]*

in November 1999 and are being carried out under the auspices of the International Permafrost Association (IPA) through its working group on Coastal and Offshore Permafrost and its coastal erosion subgroup.

Arctic Coastal Dynamics is focused on the processes that occur along permafrost-affected coasts. Of particular note are the influences of ice and permafrost (massive terrestrial ground ice, subsea permafrost, and sea ice). Results and recommendations of the Woods Hole workshop included:

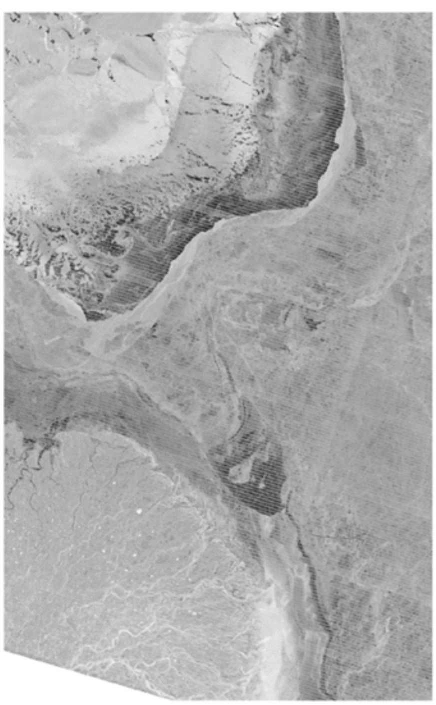
- Development of a metadata form for selecting and establishing key monitoring sites;
- Establishment of a consistent and generalized coastal classification scheme based on morphology and materials;
- Consensus on direct and indirect methodologies for estimating ground ice volumes and presentations of data on maps; and
- Preparation of a suite of standard tools and techniques for developing long-term coastal monitoring sites, including local community-based observations.

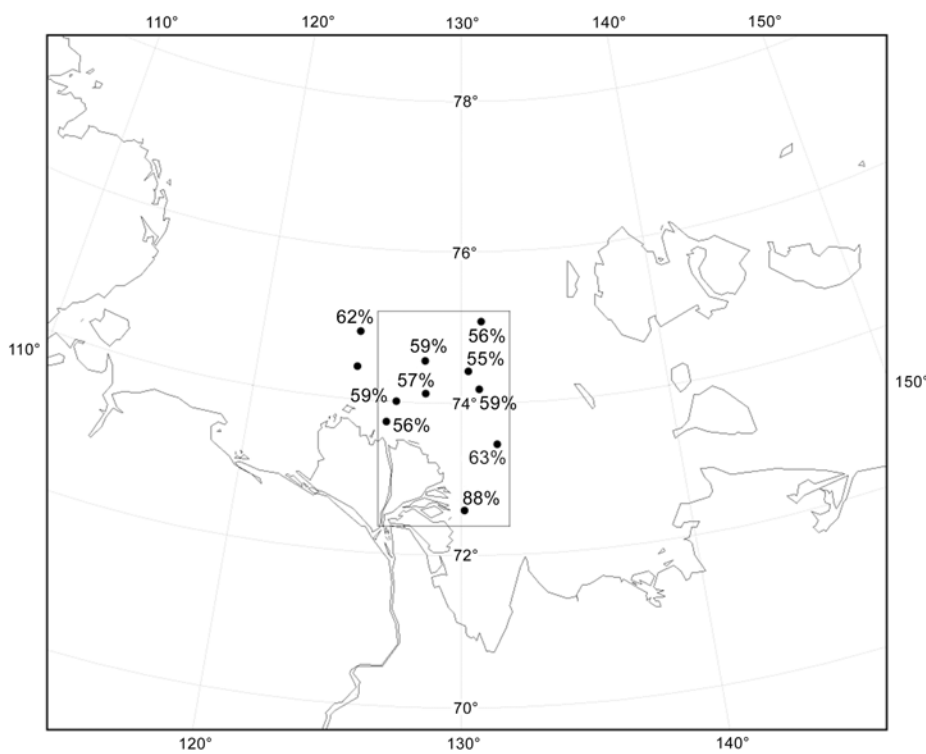
Additional workshops have been held subsequent to the original RAISE-supported workshop in Woods Hole, and the abstracts and results of these workshops are being published in *Berichte zur Polar-und Meeresforschung* (*Reports on Polar Research*). A five-year ACD Science and Implementation Plan guides the current international effort, and the program is also strongly supported by bilateral German–Russian cooperative agreements. The objectives are to improve our understanding of circumarctic coastal dynamics as a function of environmental forcing, coastal geology, cryology, and morphodynamic behavior. The science plan consists of two interrelated components:

- A series of coordinated, synthesis activities; and
- Proposed focused-research projects and long-term observations.

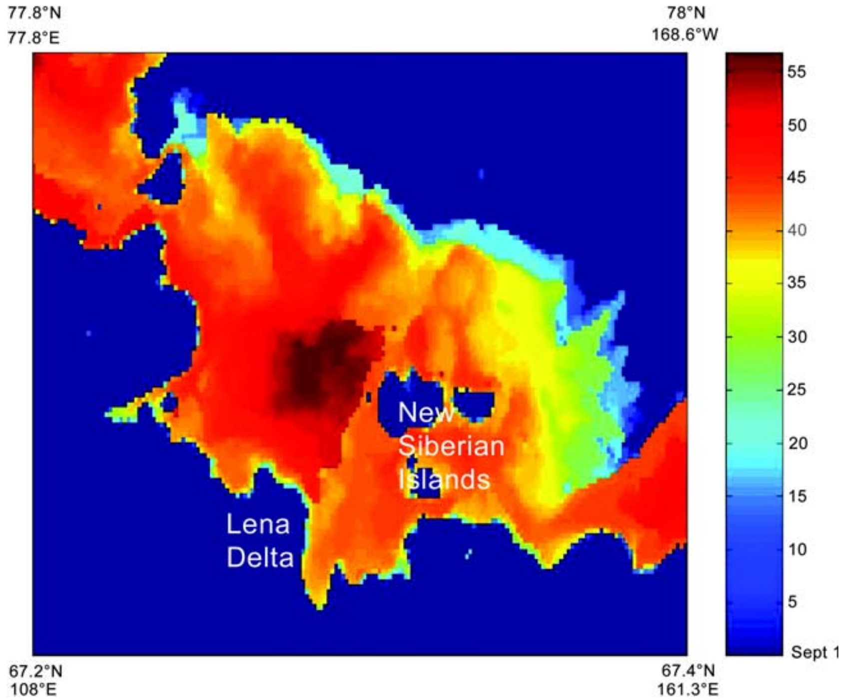
Specific scientific goals for ACD are to:

- Establish the rates and magnitudes of erosion and accumulation of Arctic coasts;
- Develop a network of long-term monitoring sites, including local community-based observational sites;
- Identify and undertake focused research on critical processes;
- Estimate the amounts of sediment and organic carbon derived from coastal erosion;
- Refine and apply an Arctic coastal classification (including ground ice, permafrost, geology etc.) in a digital form applicable to geographic information systems;
- Extract and utilize existing information on relevant environmental forcing parameters (for example, wind speed, sea level, fetch, and sea ice);

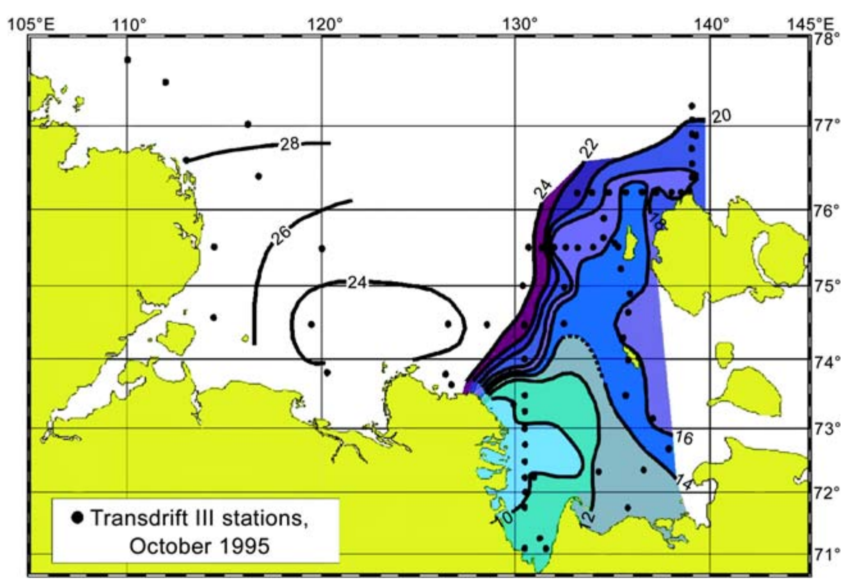




Contribution of riverine fresh water to the fast ice cover of the southern Laptev Sea. The Radarsat SAR scene (left) is coincident with the sampling program carried out in April and May 1999 (right). Locations of coring and hydrographic measurement sites are indicated along with the fraction of riverine fresh water incorporated into the fast ice cover as derived from a linear mixing model. The box on the right outlines the coverage of the SAR scene at the left.



Progression of fall freeze-up during October 1995 in the Laptev and western East Siberian Seas. The colors indicate the number of days of open water or temporary ice before final freeze-up at each location (starting September 1). Note the comparatively early onset of ice formation in waters surrounding the New Siberian Islands, bordering against a region in the west with open water persisting into late October. These patterns correspond closely to the distribution of the freshwater plume from the Lena River as shown in the panel below.



Surface salinity field of the Laptev Sea as measured during the Transdrift III ship expedition in October 1995. The numbers indicate salinity in practical salinity units (psu).

- Produce a series of thematic and derived maps (for example, coastal classification, ground ice, and sensitivity); and
- Develop empirical models to assess the sensitivity of Arctic coasts to environmental variability and human impacts.

Parallel to these coordinated, synthesis activities, focused process studies in the international program have been recommended to address varied topics, including:

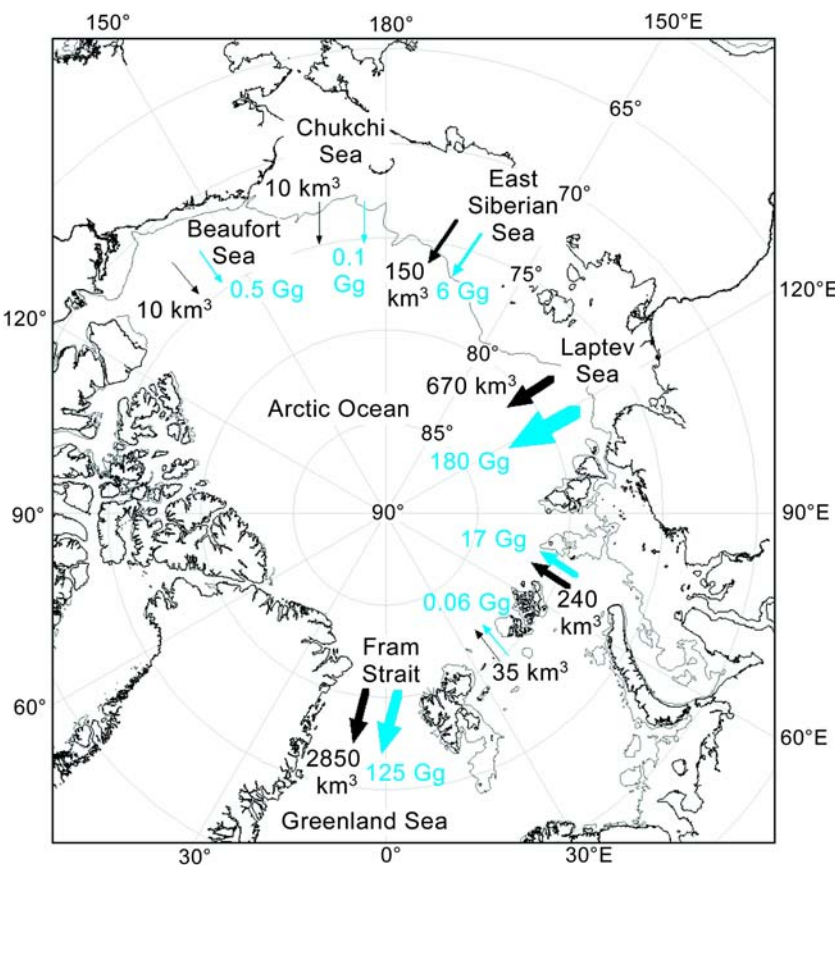
- Thaw consolidation of subsea permafrost and its role on coastal erosion;
- Weathering and erosion of bedrock;
- The fate of eroded organic carbon and sediments;
- Natural hazards and effects of human activities; and
- The role of sea ice processes in erosion and sediment transport and the influence of sea level on sediment dynamics.

Although not explicitly a part of the ACD international effort, several RAISE projects funded through NSF have addressed some of these recommended topics. For example, in one collaborative project conducted jointly with Russian scientists, the interannual variability in entrainment and transport of sediments by sea ice was investigated in the Siberian Arctic using field measurements, remote sensing, and numerical modeling (http://www.gi.alaska.edu/~eicken/he_proj/RAISE/intro. htm). In this research it was found that freshwater dispersal from the Lena and other major rivers contributes substantially (more than 60% in 1999) to the Laptev Sea fast ice cover, impacting entrainment of sediments and shelf hydrography. Overall sediment entrainment was controlled by the combination of river discharge and meteorological conditions that impact vertical mixing and lateral dispersion of low-salinity water over the shallowest portions of the shelf. While only a fraction of the sediment-laden ice is actually exported into the deeper basins, this fraction still accounts for a substantial portion of the basin-wide transport of particulates and particulate organic carbon.

Among the major accomplishments of this research was the demonstration that the combination of synthetic aperture radar (SAR) and visible- and infrared-range remote sensing can allow discrimination between the principal ice types in the coastal environment affected by substantial river runoff (freshwater ice, brackish ice, sea ice, bottom-fast ice). The combination of this comprehensive remote-sensing approach with water and ice sampling and measurements during the Russian–German Transdrift VI expedition was used to develop a first conceptual model of the transfer and interaction of freshwater and dissolved and particulate matter with the ice cover of the southern Laptev Sea and other marginal seas affected by strong freshwater input. Ice-core analyses (textural stratigraphy, salinity, and stable isotope measurements) in conjunction with sequential SAR images indicate distinct zones with a near-shore belt of freshwater and brackish ice with very low particulate and dissolved matter concentrations.

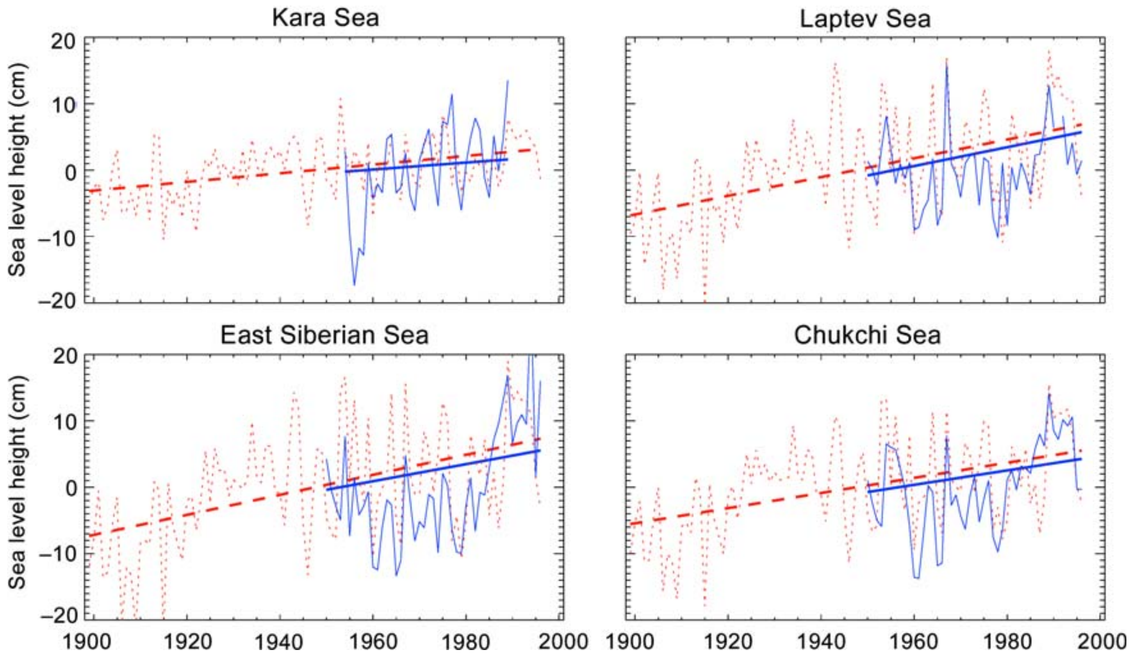
The distribution of bottom-fast ice over a broad platform extending out from the Lena River delta to the 2-m bathymetric contour is a recurring feature for the years studied with SAR data (1997–1999) and plays an important role in maintaining the location of the delta coastline. The stable isotope data clearly show that most of this near-coastal delta ice is composed of more than 80% river water. Remarkably, however, river water fractions of well above 50% were found several hundred kilometers away from the source throughout the southeastern Laptev Sea. On average, the fast ice cover in this region is made up of roughly 60% river discharge. Modeling and analysis of forcing data indicate that 1999 was not an extreme year, suggesting that a significant fraction, possibly as much as half of the total annual discharge from the Lena River, is eventually incorporated into the fast ice cover.

Annual export of first-year sea ice (black arrows and numbers) and terrigenous particulate organic carbon transported by sea ice (blue arrows and numbers).



This retention of fresh water on the shelf is significant not only for the entrainment of sediment into the sea ice cover but also for thermohaline mixing over the shelves and the adjacent basin. As further supported through the analysis of freeze-up data and the corresponding hydrography, the atmospheric circulation regime and the degree of wind mixing can determine to what extent the freshwater signal from river discharge is either released as a single pulse into the Arctic Ocean or retained and obliterated through incorporation and delayed release from the fast ice cover. At the same time, sea ice and hydrographic data analyzed as part of this study indicate that reduced mixing of fresh water and incorporation of freshened surface waters into the ice cover reduce the likelihood for sediment entrainment, underscoring the importance of a brief period during fall freeze-up for entrainment and export events.

This linkage between the atmospheric circulation regime, surface hydrography, and freeze-up patterns is evident in the entire time series and at least to some extent correlated with the larger-scale circulation patterns over the Arctic Ocean (that is, cyclonic vs. anticyclonic). Statistical and principal component analyses of these freeze-up fields indicate that ice formation is dominated by meridional gradients associated with the position of the summer ice edge and land–ocean processes. Derivation of the areal fraction of sediment-laden ice over the fast ice belt of the Laptev Sea provides some indication that these atmospheric and oceanic processes, as well as the ice freeze-up patterns, are also reflected in the distribution of sediment-laden ice. While the latter also strongly depends on water depth and synoptic sea level and (tidal) currents, maps of the interannual variability of sediment-laden ice distribution essentially confirm the hypothesis that it is the combination of river discharge and atmospheric parameters (wind direction and wind stress) that determines entrainment of sediments. A synthesis of the data collected as part of this study, as well as modeling work and review of the existing literature, indicates that the central Siberian shelf, mostly because of the combined influence of riverine and coastal input and ice production and

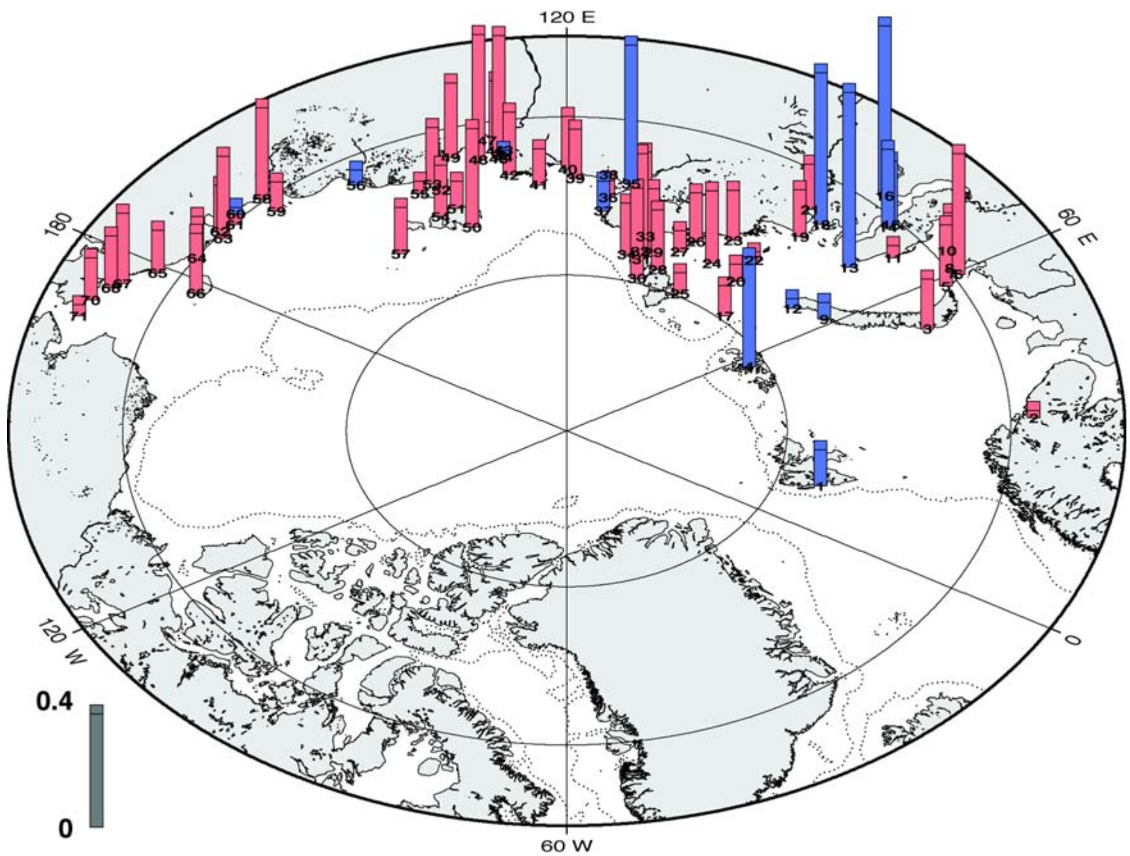


Sea level changes at some stations being used in a study of Arctic Ocean sea level change. In the graphs the solid lines show observations and the dotted lines show simulation results of a two-dimensional barotropic coupled ice–ocean model driven by monthly winds and atmospheric pressure gradients. The straight solid and dashed lines show linear trends for observed and simulated data, respectively.

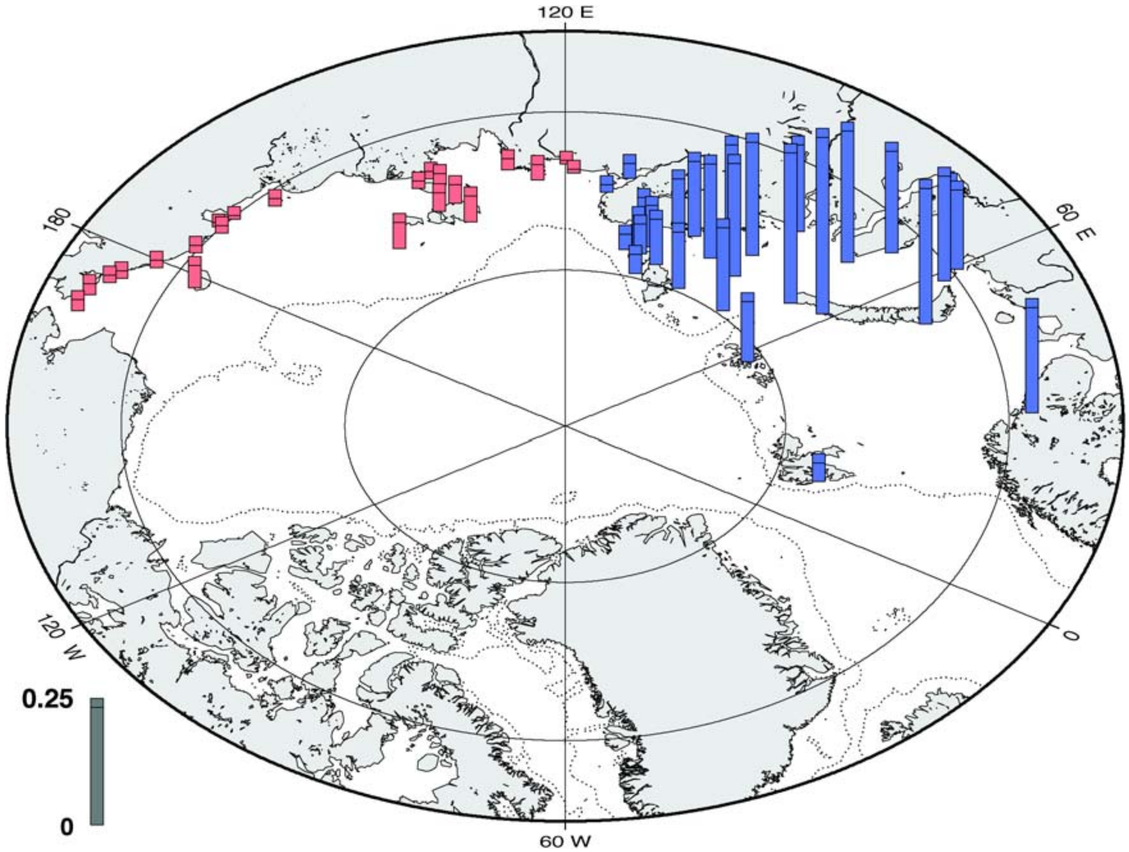
export, experiences some of the highest fluxes of particulate organic matter from the shelf into the basin observed in the Arctic.

Other research on this topic is being jointly supported through the IARC in Fairbanks and the RFBR, including studies of dissolved carbon dioxide in continental shelf waters that are establishing a link between Arctic coastal dynamic processes and the release of carbon dioxide from marine and terrestrial organic carbon.

Another aspect of coastal dynamics in the Arctic that is being addressed by a recently



Observed trends of sea level change (cm/year). Increases are in red; decreases are in blue.



Rate of sea level change caused by glacial isostatic adjustment (cm/year). The rebound of the earth surface following glacial retreat is greatest in the western portions of Eurasia that were glaciated during the Pleistocene. Increases are in red; decreases are in blue.

funded RAISE project is the significance of global warming and anticipated sea level rise impacts on shoreline erosion, sediment transport, navigation conditions, and oil and gas operations. This work is being based on analyses of existing but previously unavailable time series of sea level heights from Russian archives; atmospheric, cryospheric, terrestrial, and oceanic data sets; and the results of numerical modeling and data reconstruction. Goals include:

- Identifying links among sea level variability and atmospheric, hydrologic, cryospheric, and oceanic processes;
- Quantifying the regional and temporal variability of relevant processes in terms of sea level response; and
- Determining the relative importance of each factor influencing sea level change under global warming conditions.

There are two approaches being used:

- Investigation of the variability of sea level at seasonal and decadal time scales to estimate the secular sea level change and major factors responsible for this change; and
- Investigation of sea level variability at synoptic time scales (climatology of storm surges and their influence on coastal erosion).

Analyses of 50 years of monthly mean data from 57 tide gauges show that at the majority of stations the sea level has risen at a rate of approximately 1.4 mm/year. When the secular rates of change are corrected for the influence of glacial isostatic adjustment, the average rate of secular sea level rise is determined to be 2.3 mm/year, which is very close to the rate of 2.0 mm/year that has been determined from U.S. east coast data. Investigation of the decadal variability of sea level change using observational data and model results shows that the cumulative action of the wind-driven and thermohaline circulation may account for about 80% of sea level variance in the Arctic Ocean during 1950–1990. The most intriguing results were observed in the decade 1990–2000, when the rate of sea level rise was close to zero or became negative, contrary to the common expectation that the rate of sea level rise should increase uniformly as a consequence of global warming. This clearly warrants more detailed investigation.

Storm surge climatology of the Arctic marginal seas is being investigated based on observational data and two-dimensional coupled ice–ocean barotropic model results. The model was calibrated based on the strongest storm surges observed in the Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas, and initial results show good reproducibility with observations. It is expected that the results can be used to aid current and future scenario risk assessments of coastal flooding and costal erosion rates.

Future Directions for RAISE

Individual project proposals for work under the RAISE research priorities continue to be accepted by the Office of Polar Programs of NSF on a rolling basis. In addition to the newly funded project on sea level rise described above, a recently initiated study is assessing the impacts of disturbances such as fire on trace gas exchange with the atmosphere in Siberia.

The project management office and international steering committee funded through RAISE also perform essential functions to facilitate the exchange of information between U.S. and Russian scientists and the Arctic research community as a whole, including providing information on Russian researchers, their contact coordinates, and the activities funded by the RFBR (see http://arctic.bio.utk.edu/RAISE/Russian_projects.html). In addition, the RAISE project office participates in the exchange of information with other countries having bilateral research programs in the Russian Arctic through the IASC's International Research Initiative in the Russian Arctic (ISIRA), Land–Ocean Interations in the Russian Arctic (LOIRA), and the ACD. The project office has also been involved in developing the new coordinated land–sea margins research project (LSI) in the Arctic, which is meant to better support interdisciplinary environmental change research in the Arctic coastal zone.

Although the scale of research funding for RAISE individual projects remains relatively small, the emphasis on bilateral research in the Russian Arctic has been crucial for providing a U.S. research presence in the large portion of the Arctic that is in the Russian Federation or its offshore waters. This presence and the accumulated experience of RAISE researchers should be of great value in the future as new Arctic hydrological research programs that include work with Russian investigators are initiated (Arctic-CHAMP) and as the potential for successful, coordinated near-shore research programs, such as LSI, are developed.

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The LAII Program: Land–Atmosphere–Ice Interactions

Biocomplexity in the Arctic Terrestrial System

This article was prepared by Matthew Sturm, Chair, LAII Science Steering Committee, U.S. Army Cold Regions Research and Engineering Laboratory, Fairbanks, Alaska.

LAII stands for Land–Atmosphere–Ice Interactions. It, along with OAII (Ocean–Atmosphere–Ice Interactions), was one of the first components of the Arctic System Science (ARCSS) program at the National Science Foundation (NSF). The focus of LAII has been primarily on understanding the role of the terrestrial system in Arctic change.

For historical reasons, studies during the initial phases of LAII focused primarily on tundra and its role in the Arctic carbon budget, yet shrub tundra and boreal forest cover a significant percentage of the Arctic as well. Consequently, in recent years LAII research has expanded to include these ecosystems. Additionally, as we have come to recognize the unprecedented changes taking place throughout the Arctic, the geographic scope of the program has had to expand, extending from Alaska to the entire pan-Arctic. LAII focus, too, has broadened from carbon exchange to the exchange of energy and moisture, with some research now addressing the impact of the changing Arctic on animals and human society.

At the time of this writing, LAII is poised once again to evolve in response to new science questions and issues. A science plan has just been released for a new program called PACTS (Pan-Arctic Cycles, Transitions and Sustainability), which focuses on the vulnerability of Arctic systems and the costs of sustaining Arctic human, animal, and plant systems.

Aerial view of tundra and ice wedge polygons.

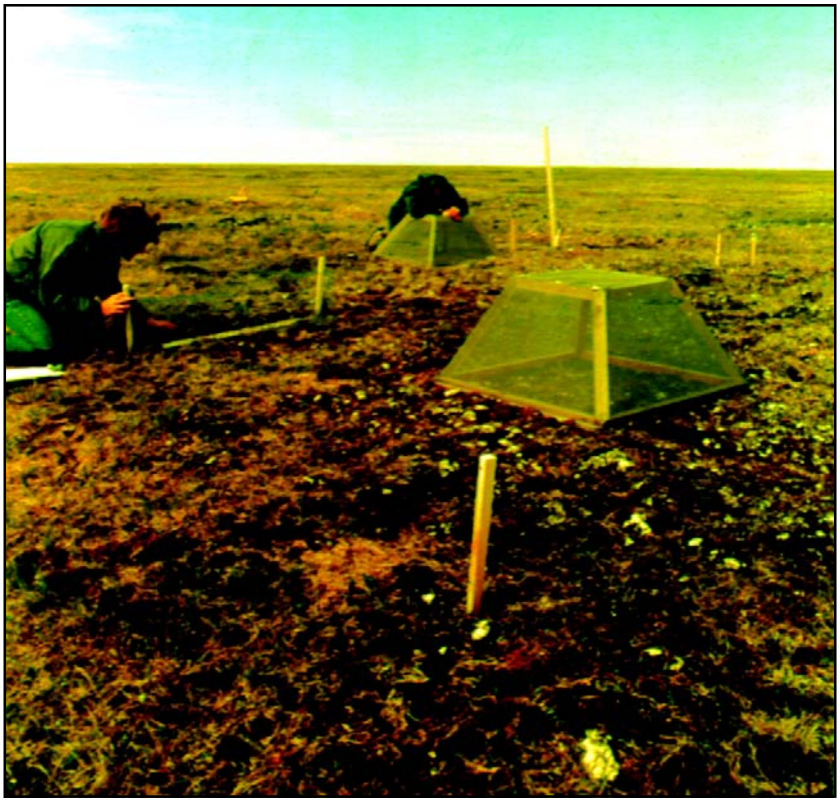
Roots of the LAII Program

Arctic tundra, covering about 6% of the land surface of the earth (about 4 million square kilometers) and 44% of the land north of the Arctic Circle, was recognized as an important land cover by the 1950s. Initial scientific interest in tundra stemmed from the fact that it survived some of the lowest temperatures and shortest growing seasons experienced by any ecosystem. Through a series of coordinated studies, it soon became apparent that tundra was linked in complex and important ways to Arctic hydrology, the thermal balance of the active layer, permafrost, and the climate through the surface energy exchange. To understand the Arctic, one had to understand the tundra. In addition, vast stores of peat underlying the tundra regions were identified as a major repository of terrestrial carbon whose fate, in some complex way, was linked to the state of the tundra and the climate.

Research was focused on several of these issues, and good progress was made. The early studies correctly identified that:

- Tundra vegetation could not be understood without also understanding the biophysical and biogeochemical linkages between the tundra and its environment and climate, and
- Changes in the tundra potentially have global effects through a number of feedbacks and linkages between the Arctic and lands farther south.

This dual focus—on change and climate and on linked biotic and abiotic systems—was well ahead of its time, predating current interest in



Tundra biome manipulation experiments near Barrow, Alaska, 1973.

linked systems and biocomplexity by about 40 years.

Excluding a few studies by individuals, the first coordinated U.S. tundra study was the U.S. IBP (International Biological Program) Tundra Biome program (1970–1974). This program set a model for subsequent programs by addressing climate, hydrology, and carbon exchange as well as the physiology and ecology of plants, microbes, and tundra fauna. It was based at the Naval Arctic Research Laboratory at Barrow, Alaska, and largely limited its focus to wet coastal tundra there.

It was followed by the RATE (Research on Arctic Tundra Environments) (1975–1978) and the R^4D (Response, Resistence, Resilience and Recovery from Disturbance) programs (1984–1987). These two programs were located farther south in drier tundra (at Atqasuk) and in the rolling foothills just north of the Brooks Range at Toolik Lake. They also had a wider focus than just tundra vegetation.

Funding for these coordinated studies varied. The Office of Naval Research funded some of the earliest studies, while the IBP was funded by NSF. NSF also funded the RATE program. R^4D was funded by the Department of Energy (DOE). In a way, all of these programs continued the trend, recognized early on, that the whole system, not just the vegetation, would need to be studied if the response of the system to disturbance or change was to be understood or predicted.

Origin and Organization of the LAII Program

The seeds for ARCSS were planted when the leaders in the U.S. Arctic global change community formulated a science initiative focus on the pan-Arctic region and climate change in 1987. When launched 1991, the ARCSS program had three components—OAII, LAII, and GISP2/PALE (the Greenland Ice Sheet Coring Program). The LAII program was developed following a workshop held in Boulder, Colorado, in 1990.

The goals of ARCSS were, and to a large extent remain, to:

- Understand the physical, geological, chemical, biological, and sociocultural processes of the Arctic system that interact with the total earth system and thus contribute to or are influenced by global change, in order to:
- Advance the scientific basis for predicting environmental change on a seasonal-to-centuries time scale and for formulating policy options in response to the anticipated impacts of global change on humans and societal support systems (http://www.nsf.gov/od/opp/arctic/system.htm).

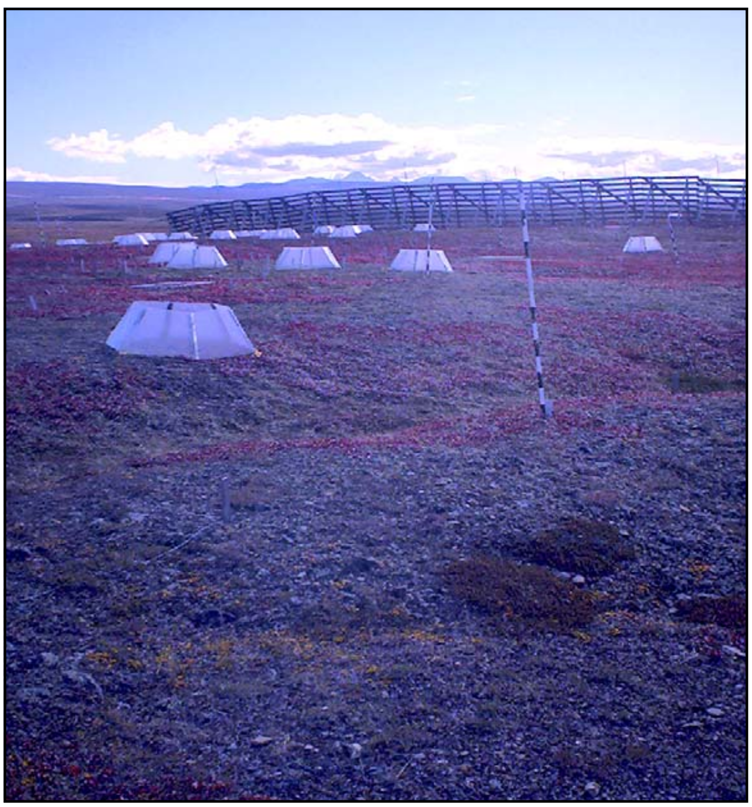
The goal of LAII has been to improve understanding of the role of interactions among land, atmosphere, and ice in the functioning of the Arctic system, with an emphasis on improving the predictability of Arctic system responses to global change. Research within LAII has been organized around four main themes:

- Detection and analysis of Arctic change;
- Circumpolar extrapolation of Arctic terrestrial climate feedbacks;
- Past and future changes in the Arctic system; and
- Sustainability of the Arctic system under global change.

The inaugural LAII initiative was called the Flux Study (1993–1998). It was followed by a second initiative called ATLAS (Arctic Transitions in the Land–Atmosphere System: 1998–2003), which is now winding down. As the Flux Study was gearing up, ITEX was also brought into the LAII program (1995). The purpose of ITEX (International Tundra Experiment) is to

A Short History of ITEX

The start of ITEX can be traced to a challenge put forward by Arthur Lachenbruch, who asked why botanists were not using plant response to monitor climate change in a fashion similar to the way permafrost was being used. From a workshop held in December 1990 emerged the basic ITEX experimental design: a standardized, simple, inexpensive phenology study that could be applied across the Arctic and that would look at organisms rather than whole systems. Small, open-top chambers would be used to passively warm tundra plants and to measure their response. Rapid progress was made, and soon the ITEX network was up and running. Shortly after its inception it became part of the UNESCO Man and the Biosphere Program's Northern Sciences Network. In the U.S., ITEX sites were located at Toolik Lake and Barrow, Alaska, as well as in the alpine tundra of Colorado. In 1995 the U.S. contribution to ITEX was brought into the LAII program as a companion to the Flux Study. Over time the first simple ITEX experimental protocol has been expanded to include more sophisticated measurements and manipulations involving whole system responses. As the Flux Study evolved into the ATLAS program, ITEX evolved into NATEX (North American Tundra Experiment), with a more extended ecosystem response as its focus. NATEX is still an integral part of the ITEX network, which, with over 20 sites in 13 countries, is one of the few truly circum-Arctic research programs.



A set of ITEX cones on the tundra near Toolik Lake, Alaska. In the background is a snow fence designed to test the effect of increased snow on the tundra.

monitor the performance of plant species and communities on a circumpolar basis in undisturbed habitats with and without environmental manipulations. The U.S. effort under ITEX (which eventually came to be called NATEX, the North America Tundra Experiment) was seen as a logical and complementary addition to the Flux Study, which also had a strong focus on tundra plants. In addition, more than a dozen projects that did not fit neatly into these two larger initiatives, but nonetheless addressed the core issues of LAII, were also brought into the program.

From its inception, LAII has been operated by the research scientists themselves in cooperation with the ARCSS program manager. A Science Steering Committee (SSC) with about 10 members works in partnership with a Science Management Office (SMO), currently at the Center for Global Change and Arctic System Research at the University of Alaska Fairbanks. The SSC and the SMO provide scientific leadership and science planning for LAII activities. During the active phases of both the Flux and ATLAS initiatives, they also developed and implemented coordinated field plans, with the assistance of the NSF Arctic logistics contract* in order to ensure full integration between projects.

The SSC has emphasized integration across the wide array of disciplines represented in LAII. This successful blending of ecology, biology, geophysics, atmospheric sciences, and glaciology has been a significant accomplishment of the program as a whole. It has come about through coordinated field studies and has been promoted by organizing special sessions at national meetings, by compiling special journal issues, by developing data CDs (through JOSS, the Joint Office for Science Support in Boulder, Colorado), and by organizing working retreats for investigators. The LAII web site (http://www.laii.uaf.edu) maintained by the SMO is an excellent source of information on these synthesis activities and the projects that make up LAII. Two television documentaries, produced in conjunction with KUAC-TV in Fairbanks, Alaska, provide good overviews of LAII research and the multidisciplinary work that has been required to achieve results.

LAII Initiatives

In the initial phase of LAII, 28 projects were funded. Thirteen projects comprised the Flux

* Currently VECO Polar Resources

The San Diego State University Sky Arrow aircraft in Barrow, Alaska, prior to a flight to measure CO_2 and other concentrations and fluxes along a traverse line over the tundra as part of the ATLAS project. In the Flux Study, a slightly different aircraft was used.

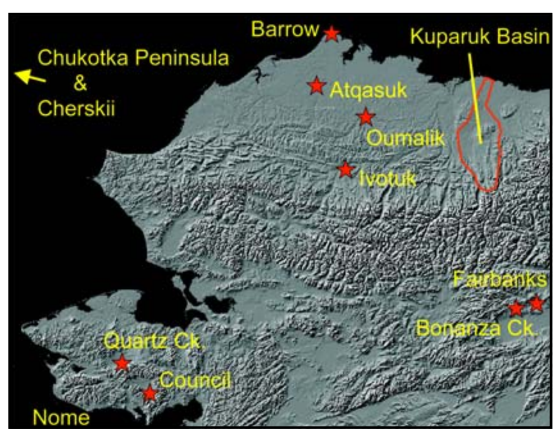
Study, all focused on the Kuparuk River Basin on the North Slope of Alaska. This 9000-square-kilometer basin (an area the size of the Netherlands) extends from the Arctic coast near Prudhoe Bay south to the Brooks Range and includes Toolik Lake Field Station, perhaps the largest U.S. Arctic research station, operated by the University of Alaska.

In concert, the 13 projects investigated the variables and processes controlling the fluxes of carbon dioxide (CO_2), methane (CH_4), water, energy, and nutrients between the watershed and the atmosphere. The study emphasized spatial scaling, working from plot to watershed. Several methods of scaling up were used. For the exchange of carbon dioxide between the atmosphere and the tundra and the freshwater system, point measurements were made using chambers and eddy flux towers. The towers were moved from one vegetation type to another, remaining in residence long enough to determine the variation in flux during a range of representative growing season conditions. By the end of the project, virtually all of the main types of vegetation found on the Arctic Slope of Alaska had been sampled. Aircraft fitted with open-path infrared gas analyzers were used to make measurements along traverse lines of tens to hundreds of kilometers. For snow cover, hydrology, active layer thickness, and vegetation, spatial scaling was done using spot sampling, traverses, and satellite data. From relationships developed from the measurements, water, energy, methane, and CO_2 fluxes were extrapolated over the entire basin using maps of topography and vegetation and gridded fields of weather data. Both experimental and modeling results were summarized in a special issue of the *Journal of Geophysical Research*.

An eddy flux tower used to measure the weather and the flux of CO_2 and moisture from the tundra to the atmosphere.

The second phase of LAII consisted of a major coordinated study called ATLAS, involving more than 25 universities, and the continuation of ITEX. Like the Flux Study, ATLAS research focused on fluxes of CO_2, water, and energy between Arctic terrestrial ecosystems and the atmosphere and oceans, but this time the goal was to understand how these fluxes varied across transition zones between ecosystems and at vegetation boundaries. Seven intensive research sites were established, with five sites located in Alaska and two sites located in the Russian Far East. Studies conducted at these sites were complementary with research being done along the network of high-latitude transects established by the International Geosphere–Biosphere Programme (IGBP) and at the two Long Term Ecological Research (LTER) sites in Alaska (Toolik Lake and Bonanza Creek).

The ATLAS program built directly on the Flux Study results. Extrapolations and models developed in the Kuparuk Basin were applied and tested on a parallel transect line running from Ivotuk to Barrow. ATLAS also employed the concept of "space for time" by making measurements at Council near Nome, Alaska. Council is warmer and moister and has more extensive coverage of shrubs than the Arctic Slope, with treeline nearby. These conditions were thought to be a reasonable analog for what the conditions on the Arctic Slope might be like if the climate continued to warm. The sites in Russia provided opportunities

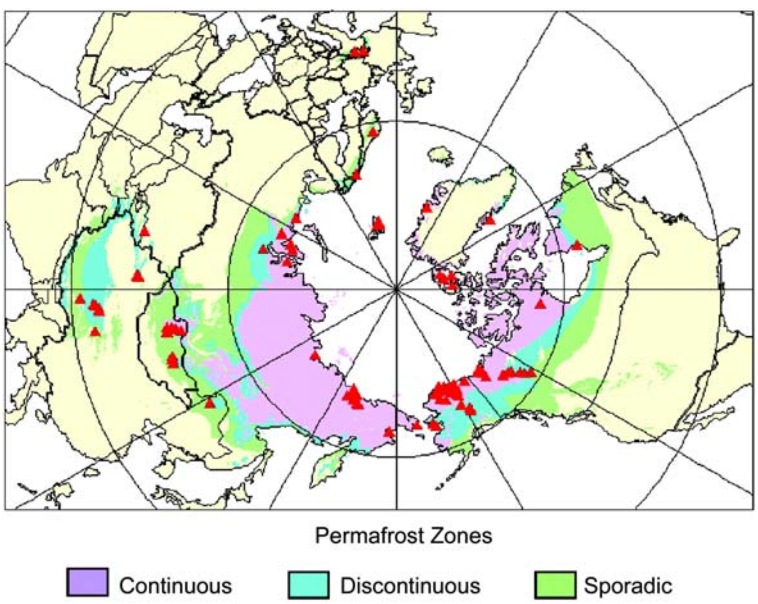


Sites studied in northwestern Alaska during the Flux Study and ATLAS programs.

The Circumpolar Active Layer Monitoring Program

The Circumpolar Active Layer Monitoring program, known as CALM, was based on ideas developed at an international symposium held in West Siberia in 1989 and is modeled in many ways on the ITEX network. The goal of the program is to observe the long-term response of the active layer and near-surface permafrost to changes in climate. The most difficult part of implementing the program was building an alliance of active field scientists willing to both share their data and adopt a set of standardized protocols. Despite these difficulties, by 1995 the fledgling circum-Arctic network was up and running.

Under ATLAS the network has expanded rapidly with the addition of several Alaskan sites. The most significant expansion, however, occurred when NSF (through the CALM program) was able to provide funding for 23 sites in Russia. Existing or newly developed sites in Canada, China, Greenland, Kazakhstan, Mongolia, Norway (Svalbard), Sweden, Switzerland, and Antarctica were also brought into the program, making it both bipolar and circumpolar. The CALM network now includes more than 100 stations, operated by scientists from 15 countries. The program is administered at the University of Cincinnati, where a web site is maintained (http://k2.gissa.uc.edu/~kenhinke/CALM/). Only a little more than a decade into its existence, CALM has already produced a large body of scientific literature. In addition, data produced from the CALM network has proven useful in model validation. Activity under the CALM program reached its apogee in late 2002, when 35 scientists from 6 countries attended a workshop at the University of Delaware, where scientists had an opportunity to discuss progress and plan future activities. A workshop report will be issued in 2003, and a group of papers presented at the workshop is in preparation for publication in *Permafrost and Periglacial Processes*.



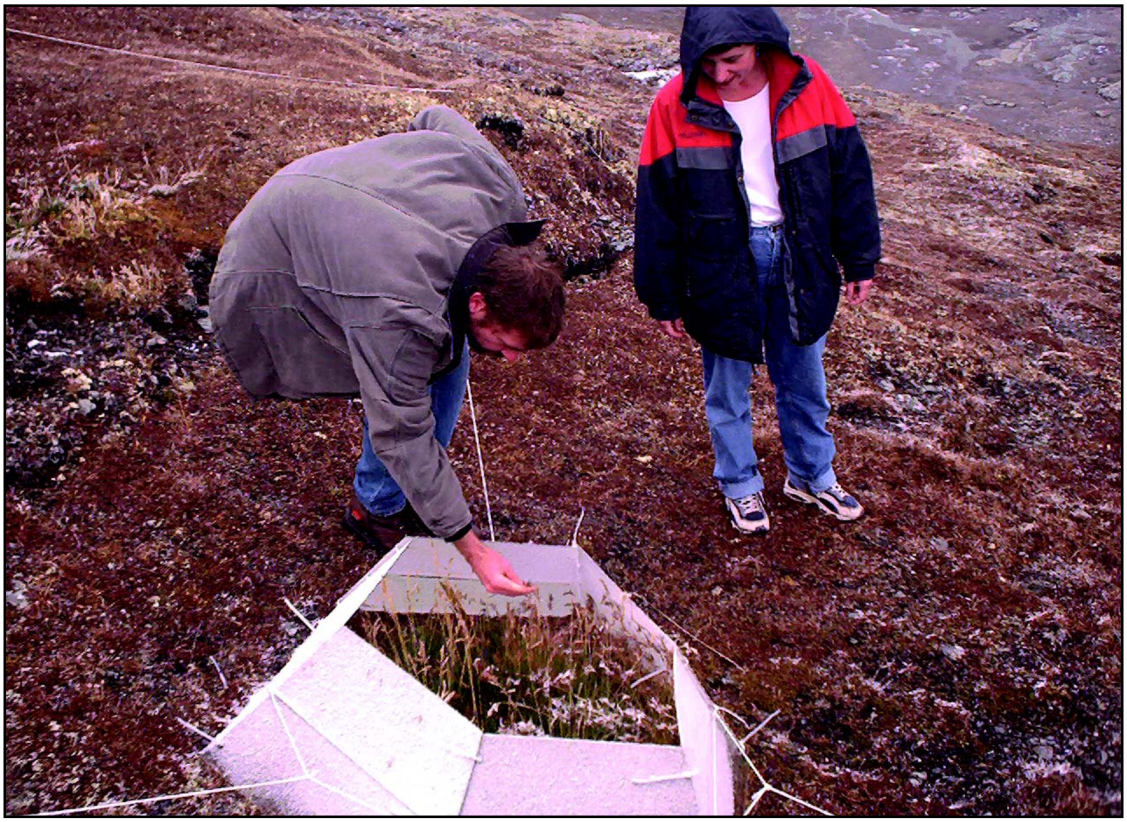
Location of CALM sites in the Arctic, with permafrost distribution also shown.

for comparative studies of tundra under different regimes of climate change and of processes in transitional ecosystems between tundra and boreal forest. The site on the Chukotka Peninsula has not experienced warming, unlike the sites at Council and Quartz Creek. The other Russian site (Cherskii) is in a transitional ecosystem between tundra and larch forest not represented in Alaska.

Using data from these sites, modeling efforts, including both retrospective analyses and regional and global climate model sensitivity experiments, have investigated potential future scenarios for the Arctic over the next 10–200 years. To achieve greater pan-Arctic coverage, both the Flux Study and ATLAS research have been integrated with studies from Canada (BOREAS: Boreal Ecosystem–Atmosphere Study). Some of these extrapolations were published in a special issue of *Global Change Biology* in 2000. Initial results related to the space-for-time part of ATLAS are summarized in a special issue of the *Journal of Geophysical Research* currently in press; because the program is just ending, the data are still being analyzed. Data from the Barrow–Ivotuk transect have been issued in a user-friendly CD.

Six U.S.-funded projects made up LAII's latest contribution to ITEX. The initial results from these projects, as well as their international ITEX counterparts, have been synthesized. ITEX researchers have also led the development of global comparisons of the warming response of terrestrial ecosystems, through the development of networks like the GCTE global change and terrestrial ecosystems Network of Ecosystem Warming Studies (NEWS).

LAII has also been home to a number of independent projects. Notable among these were projects that focused on atmospheric processes and their interactions with ice and snow, projects that examined synoptic-scale climate analyses, and projects that focused on permafrost dynamics and the human dimensions of global change. A wide range of other topics were also funded. These include historical and paleo-reconstructions of climate, vegetation, biogeochemistry, and permafrost; process studies of soil heat flux, biogeochemistry, and treeline movement; circum-Arctic hydrologic analyses; studies of the sustainability of Arctic communities; and modeling and synthesis activities. One of the most notable independent projects was CALM, in which a series of circum-Arctic sites were developed for monitoring changes in active layer thickness. This network currently includes more than 100 sites in 15 countries.



An ITEX cone, where warming has caused the plants within to grow more vigorously than the surrounding tundra.

Significant Findings

A decade of integrated research within LAII has substantially improved our understanding of the role of land–atmosphere–ice interactions in the Arctic system. Below are some key findings from the various components of LAII.

Flux Study and ATLAS

- The Alaskan Arctic has warmed significantly in the last 30 years, with associated warming of permafrost, expansion of shrub ranges (and treeline in some locations), and a temporary increase in CO_2 efflux.
- Winter is a more important period of biological activity than previously appreciated. Biotic processes, including shrub expansion and decomposition, have significant effects on winter processes, including snow structure and accumulation and the annual carbon budget of ecosystems.
- Observed vegetation changes can have a significant positive feedback to regional warming. These vegetation effects are, however, less strong than those exerted by land–ocean heating contrasts and the topographic constraints on air mass movements.

ITEX

- Experimental warming initially increased growth in most Arctic plants, particularly in shrubs, the growth form that has greatest impact on Arctic feedbacks to climate (through changes in carbon storage and energy exchange).
- At many sites the growth response to warming diminishes over time, suggesting long-term limitation of growth by other factors. The sustainability of the warming response may differ between the Low and High Arctic, perhaps indicating different long-term limitations of growth with latitude. Both the timing and the magnitude of the flowering response differ from the growth response to warming, suggesting different effects of climate on growth vs. reproduction and dispersal.

Independently Funded Projects

- All thaw lake basins sampled on the Alaskan North Slope are younger than 5000 years old. Ground ice and organic carbon accumulate following lake drainage events.
- The duration of lake ice cover (seasonal or multiyear) is a dominant control on the bio-

geochemistry of Arctic lakes. Paleoclimate sediment core proxies can therefore determine the duration of lake ice cover, and modern process studies and modeling can use this information to determine the climatic conditions necessary to sustain it.

- Circumpolar Active Layer Monitoring (CALM) shows that the active layer depth responds sensitively to summer climate, increasing in warm years and decreasing in cold years.
- Patterns of treeline response to twentieth century warming show that spruce began to invade tundra throughout Alaska after 1850, that the advance started earliest in central Alaska and more recently on the Seward Peninsula and in Alaska Range, and that spruce invasion of permafrost-affected tundra depends on melting of permafrost in some sites.

The Future

As our understanding of Arctic change has increased and as we have identified more and more aspects of the Arctic ecosystem that seem to be changing in unprecedented ways—ways that directly impact living things—the need to document and understand these changes has increased. Scientists can expect to be called on even more in the future to provide data and knowledge to leaders and policy makers as they grapple with the consequences of change. In particular, we need to learn through research how vulnerable the Arctic system is and what the costs might be of sustaining biotic systems and human society in the face of change.

These pressing questions, which grew directly out of LAII research, have led to the development of a new science plan, a blueprint for future research that begins where LAII research has ended. The program envisioned in the plan, called PACTS (Pan-Arctic Cycles, Transitions, and Sustainability), focuses on two critical questions that will take on increasing importance as the Arctic continues to change:

- How vulnerable are current Arctic ecosystems and food webs, and what will it require to sustain Arctic societies in the face of environmental change?
- How will changes in Arctic biogeochemical cycles and biophysical feedback processes affect both Arctic and global systems?

These may be the questions that fuel the next decade of research on the interaction of biotic and abiotic systems in the Arctic.

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PARCS: Paleoenvironmental Arctic Sciences

Taking the Long View of the Arctic System

This article was prepared by Glen MacDonald, Department of Geography, University of California at Los Angeles; Darrell Kaufman, Department of Geology, Northern Arizona University, Flagstaff; Matt Duvall, Department of Geology, Bates College, Lewiston, Maine; and Larry Coats, Department of Geology, Northern Arizona University, Flagstaff.

The importance of understanding the environmental history of the Arctic and placing recent and future environmental changes within the longer historical context has long been recognized as a crucial component of the NSF Arctic System Science initiative. The Paleoenvironmental Arctic Sciences (PARCS) program of ARCSS brings together a diverse community of natural scientists to identify the most important cross-cutting questions of how the Arctic system has evolved over time scales ranging from decades to millennia, and it generates research efforts to address those questions by acquiring and analyzing biological and physical records of past climate and environment. Without understanding the natural long-term variability of the Arctic environment, it is impossible to anticipate future conditions or demarcate when human-induced changes have exceeded the range of natural variability. Historical and instrumental environmental records, such as meteorological observations, are too short in duration and too sparse in geographic distribution to provide the needed long-term records of the Arctic environmental system. PARCS scientists develop and apply the research tools needed to produce and analyze records of climatic and environmental change that extend back far beyond the short time period covered by instrumental records.

The present PARCS program arose in 1999 from the amalgamation of the highly successful Greenland Ice Sheet Project (GISP2) and the Paleoclimate of Arctic Lakes and Estuaries (PALE) project. The creation of PARCS was guided by the global change imperatives of both the ARCSS program and the NSF Earth Systems History (ESH) program of the Atmospheric Sciences Division. The founding of PARCS, the creation of its structure, and the identification of a key set of research initiatives arose from a series of community-wide meetings held in 1998 and 1999 and are presented in the document *PARCS: Arctic Paleosciences in the Context of Global Change* (available at http://www.ngdc.noaa.gov/paleo/parcs/parcs.html).

Structure

The PARCS structure consists of a Science Steering Committee (SSC) with two co-chairs selected by community consensus and consultation with ARCSS. The SSC and its co-chairs are drawn from the ranks of PARCS principal investigators. The SSC oversees a science management officer and a data management officer. The latter is responsible for the timely archival of PARCS-generated data, distribution of data to PARCS and ARCSS researchers, and transmission of data to other national and international data centers. The SSC, its co-chairs, and the science and data management officers also foster and maintain ties to relevant international programs such as the International Geosphere–Biosphere Programme's PAGES paleoclimate program and Circumpolar Arctic PaleoEnvironments (CAPE) program. PARCS SSC and organizational activities are funded through grants from ARCSS. PARCS research is funded through several programs at NSF, primarily ARCSS and Arctic Natural Sciences. Most PARCS principal investigators submit grant proposals to the ESH program, where their Arctic-focused investigations are integrated into a broader network of similar research on a global scale.

General Research Imperatives

The PARCS founding document identified five general research imperatives that are fundamental to understanding the long-term functioning of the Arctic system and are of broad relevance to the wider ARCSS and global change communities. These imperatives are:

- Describe and understand the range of natural environmental variability in the Arctic at temporal and spatial scales relevant for anticipating future changes;
- Evaluate the impact and cause of climatic

"surprises" (that is, unexpected, extreme, and/or abrupt events) in Arctic climate system behavior;

- Determine and understand the sensitivity of the Arctic to altered forcings, both natural and anthropogenic;
- Document the history and controlling mechanisms of biogeochemical cycling of nutrients and environmentally sensitive species; and
- Evaluate the realism of state-of-the-art numerical models being used to predict future climate and environmental change on regional to global scales.

To address these research imperatives and to prioritize research needs, a community-wide meeting was held in 2000. Two research foci were developed to concentrate scientific efforts on the most critical questions needed to address the broader imperatives. The two current research foci are:

- Acquisition and analysis of paleoclimatic and paleoenvironmental records, linked with climate model experiments, to determine the causes and consequences of past warm episodes in Arctic climate; and
- Acquisition and analysis of high-temporal-resolution paleoclimatic records to determine the natural modes of climate variability that have impacted the Arctic over the past 2000 years and beyond.

Paleoclimatic and paleoenvironmental data from sources such as the Greenland ice cores, lake sediments, peat and soils, and other natural archives reveal that the Arctic has experienced periods when the climate was warmer than during the past 100 years. These intervals lasted from hundreds to thousands of years and took place during the present interglacial epoch (the Holocene, roughly the last 11,000 years) and during the height of the last interglacial period (some 130,000 years ago). The average summer temperatures during these warming events were 2–5°C higher than the twentieth century average. Such warm periods were caused by natural factors involving variations in the earth's orbital geometry that increased summer insolation at high latitudes. Although none of these past warm periods are a perfect analog for the warming anticipated to result from increased greenhouse gasses, they do provide evidence of the natural range of Arctic thermal variability and crucial insights into how the regional climates, ice and snow cover, permafrost conditions, and flora and fauna of the Arctic respond to prolonged and pronounced warming. Such insights are invaluable in anticipating and attempting to mitigate the future impacts of greenhouse warming.

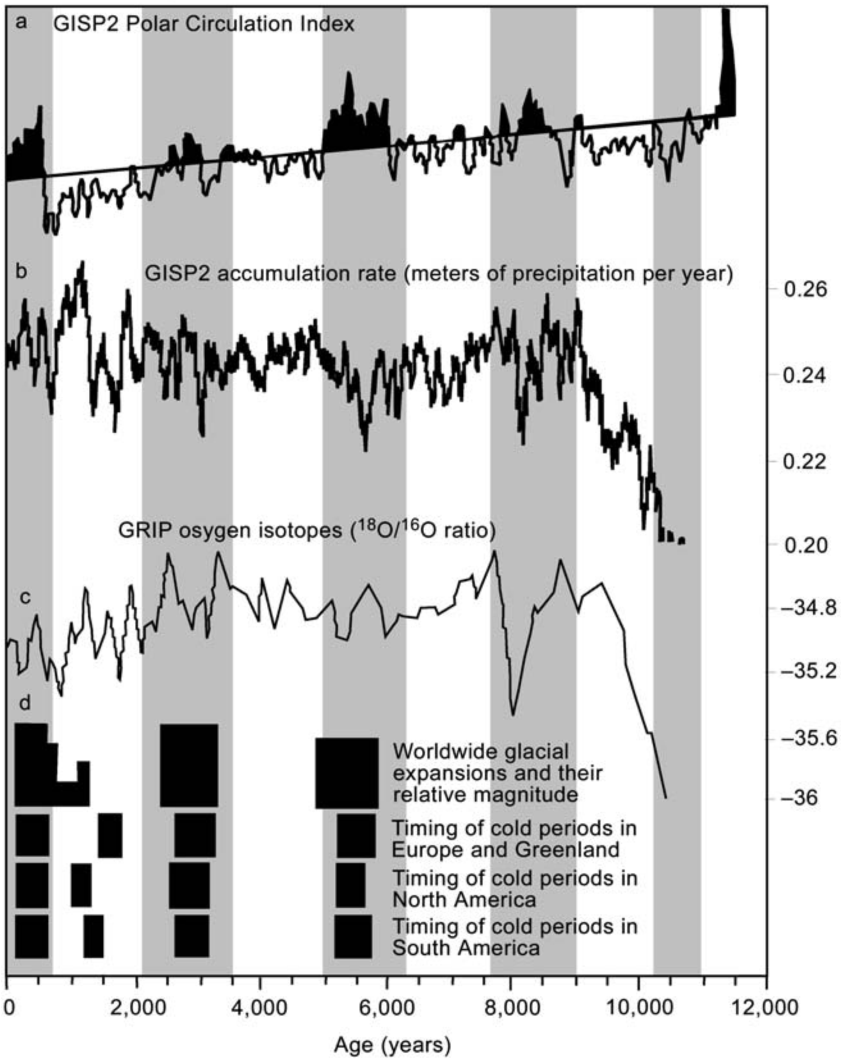
Some records of past climate, such as tree rings, lake sediments, and glacial ice, contain annual banding, allowing reconstruction of highly resolved records that have revealed natural decadal to centennial variations in Arctic climate. While the geographic patterns of these variations and their causes remain topics of intense research, we can anticipate that such natural variability will continue in the future. Understanding this long-term variability is necessary for detecting and predicting the impacts of greenhouse warming and for designing resource management strategies for the Arctic. The natural variability experienced over the past 2000 years provides a benchmark of what we may anticipate in the near future.

Recent and Current Activities

To effectively and efficiently address the two research foci, PARCS recently organized a series of working group meetings to:

- Synthesize existing data on past episodes of Arctic warming and high-frequency modes of Arctic climate variability;
- Combine these records with observational climate data and climate model experiments to help resolve the causes and impacts of past warming and high-frequency variability in climate;
- Determine the gaps in our data sets and theoretical knowledge regarding Arctic warm episodes and high-frequency climate variability; and
- Develop research synergy, strategy, and collaboration both nationally and internationally to fill the existing gaps over the next three to five years.

The first meeting was held in Maine in October 2002 and involved over 20 scientists examining the pronounced warming experienced during the height of the last interglacial period 130,000 years ago. The other two meetings were held simultaneously in Boulder, Colorado, in November 2002 and included over 30 scientists. One working group examined the timing and magnitude of maximum warming around the Arctic during the past 10,000 years, while the other working group synthesized annually resolved records of high-frequency variability in Arctic climate over the past 1000 years and compared



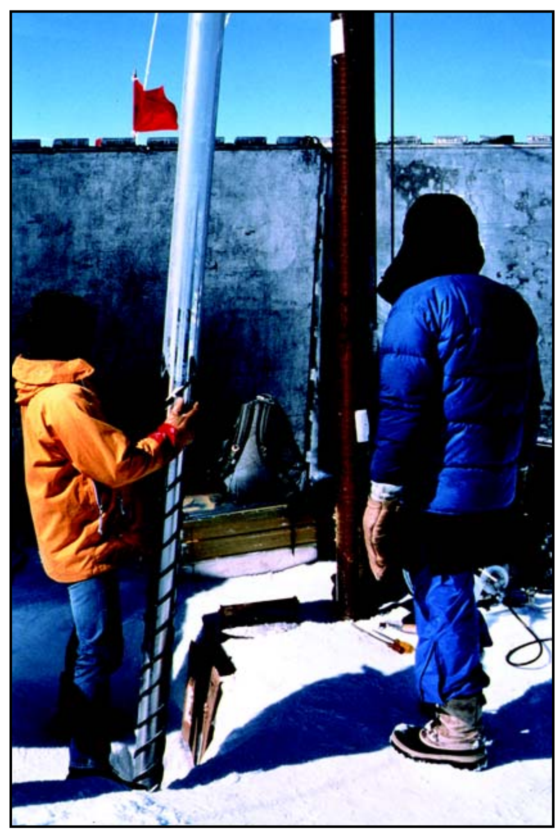
Paleoclimate information from Greenland ice cores. GISP2 PCI (a) is an index of polar atmospheric circulation intensity derived from analyses of major ion concentrations in the core. Rates of snow accumulation at the GISP2 core site (b) varied on decadal to centennial time scales. The relative concentration of the isotope ^{18}O in the Greenland ice cores (c) is related to air temperature, with lower values (top of scale) indicating warmer periods and higher values (bottom of scale) indicating cooler periods. Oxygen isotope analysis of the GISP2 core reveals increasing temperatures at the start of the Holocene and decreasing values after 4000 years ago. Superimposed on this general pattern are a number of shorter-term variations. Increased intensity of polar circulation and decreased snow accumulation on Greenland appear to be correlated with cooling and glacial advance around the globe (d).

this to known patterns of variability from instrumental meteorological records. These meetings spurred on a number of new research proposals and the preparation of five scientific manuscripts on the topics of natural warmth and variability in Arctic climate.

Examples of Recent Research Accomplishments

Paleoenvironmental scientists working in the Arctic have made major contributions to understanding Arctic climate dynamics and environmental response that are crucial to current research by a broad spectrum of ARCSS scientists and beyond. A few examples are discussed below.

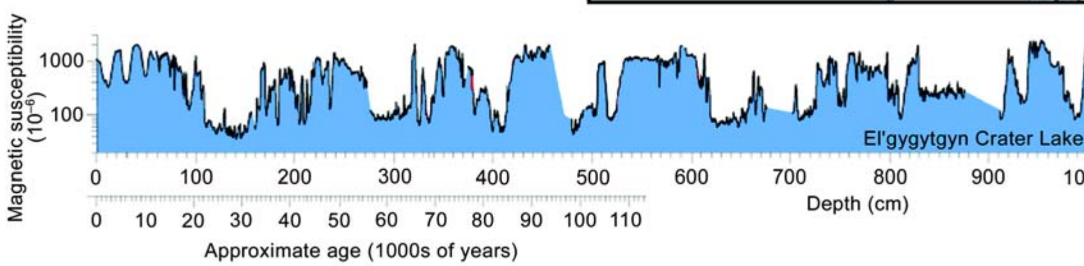
The GISP2 ice cores from the summit of the Greenland Ice Sheet provided the premier records of regional to global climate change that extend back over 130,000 years. This research has resulted in hundreds of scientific publications that have revolutionized our understanding of climate variability. Oxygen isotope records from the ice cores capture cool and oscillating temperatures during



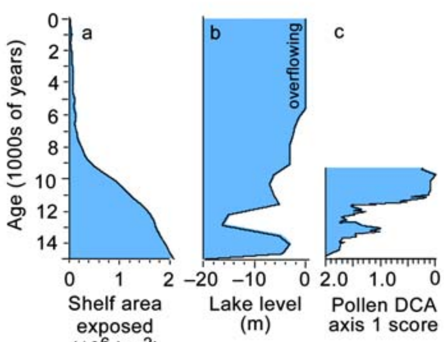
Researchers extracting an ice core at the GISP2 site.

the last glacial period and the general postglacial warming of the Arctic that commenced some 12,000 years ago. The ice cores also reveal natural changes in atmospheric concentrations of greenhouse gasses such as methane and show that the concentration of these gasses was never as high during the past 130,000 years as it is today. The ice cores show that both temperatures and precipitation rates varied abruptly and dramatically on decadal time scales. Thus, the ice cores encapsulate information on both long-term periods of warmth and shorter-term climatic fluctuations that can be compared with records from the Arctic and elsewhere. Aside from information on temperature, hydrologic balance, and atmospheric gasses, detailed chemical analyses of the ice cores have provided insights into phenomena such as past volcanic activity, biomass burning, sea ice extent, and intensity of polar atmospheric circulation.

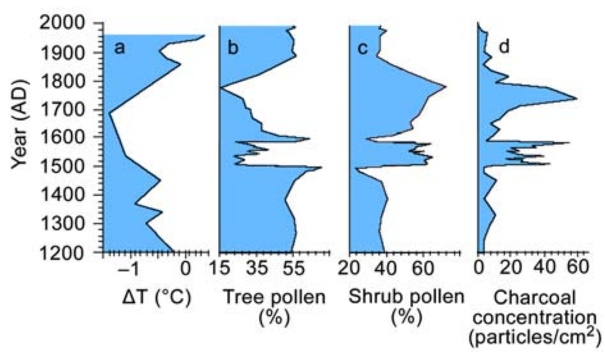
The Beringian region, encompassing Alaska and eastern Siberia, has long been a center of research by the former PALE program, which operated in tandem with the GISP2 project and was merged into current PARCS research. Recent discoveries have provided new insight into the impacts of natural climatic variability on time scales ranging from tens of thousands of years to decades across a region sensitive to fluctuations in the ocean–atmospheric circulation of the North Pacific basin. Unlike other high-latitude land areas, Beringia remained largely free of erosive glacial ice during past global glaciations, so unusually long records of paleoenvironmental changes are preserved. For example, an international team of scientists, including PARCS researchers, recently obtained a 300,000-year record from Lake El’gygytgyn in northeastern Siberia. Distinct fluctuations in a variety of physical and biological parameters indicate pronounced



Long records of paleoenvironmental change from Beringia. The graph shows the magnetic susceptibility of lake sediment from Lake El’gygytgyn, northeastern Siberia during the past two glacial-interglacial cycles. Changes in magnetic susceptibility reflect a complex system of deposition, preservation, and decomposition of organic matter and magnetic minerals.



Millennial-scale paleoenvironmental changes in Alaska. (a) Approximate extent of continental shelf area exposed as shorelines transgressed the Bering and Chukchi platforms, based on eustatic sea-level record and present-day bathymetry. (b) Lake-level changes at Birch Lake, interior Alaska, reflecting changes in effective moisture (Reprinted from Quaternary Research *53, Abbot et al., Lake level reconstructions and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects, 154-166, 2000, with permission from Elsevier). (c) Detrended correspondence analysis (DCA) of pollen assemblages from Nimgun Lake, Ahklun Mountains, southwestern Alaska; DCA axis 1 is correlated with plant taxa associated with dry soils.*

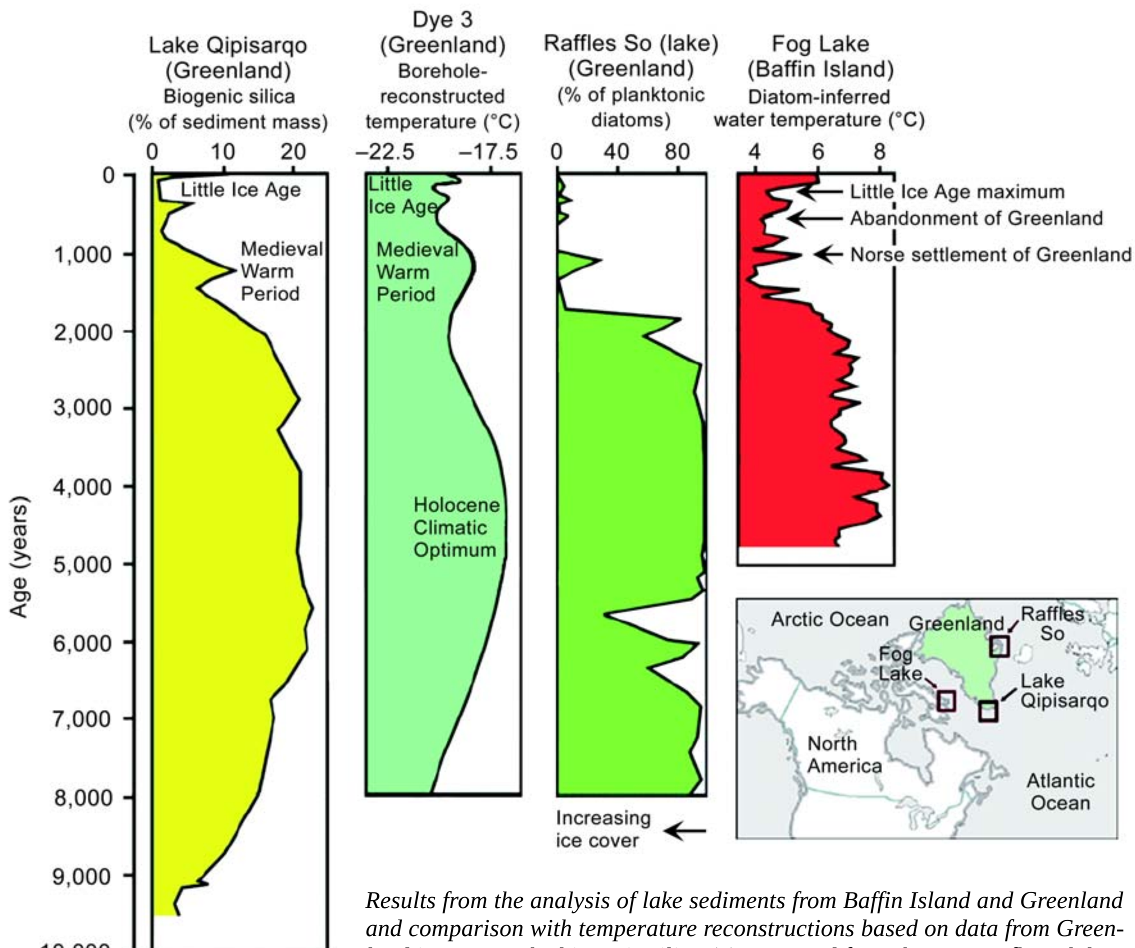


Centennial-scale paleoenvironmental records from Alaska. (a) Temperature change (ΔT) relative to the average for the twentieth century from Farewell Lake, northwestern Alaska Range, Alaska, based on oxygen-isotope analyses of abiotic and ostracode calcite. (b) Tree pollen percentage from Grizzly Lake, Alaska compared to (c) shrub pollen and (d) charcoal concentration. Wetter periods display a pattern of increased tree pollen, decreased shrub pollen, and lower fire frequency, while dryer periods show the opposite pattern.

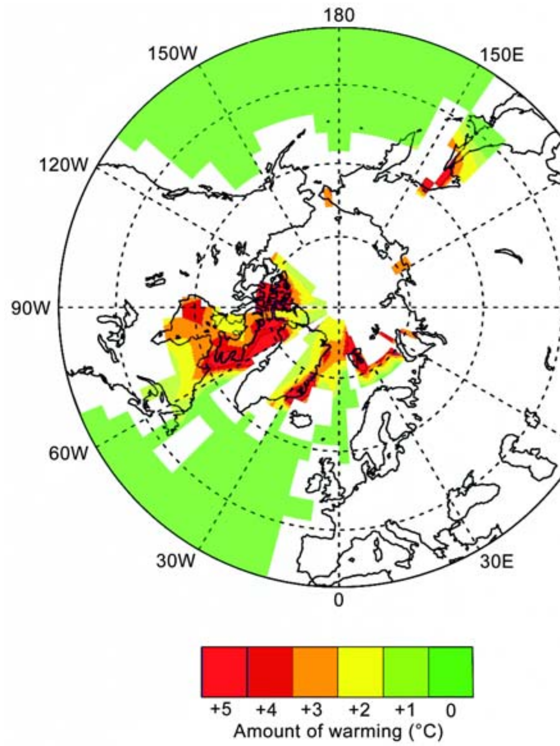
paleoenvironmental changes on millennial time scales. Variations in the magnetic susceptibility of lake sediment can be correlated in detail with oxygen isotope variations in marine sediment and glacier ice from the North Atlantic region, indicating that this is the longest continuous terrestrial record of climatic change from the Arctic.

Climatic fluctuations on centennial time scales during the last glacial-to-interglacial transition (15,000–10,000 years ago) are also now clearly documented in Alaska, where they occurred synchronously with rapid climate changes known from other high-latitude regions, suggesting a tightly coupled Arctic system. These climatic changes, along with the rise of sea level over the continental shelves of the Bering and Chukchi Seas, dramatically altered the moisture balance of terrestrial and aquatic systems across Beringia. All physical and biological aspects of the Arctic system were impacted by the dramatic climatic changes of the last glacial–interglacial transition, including the limnology of lakes, the composition of terrestrial vegetation, and the rates of land surface processes. For example, pollen data indicate that tundra plants responded rapidly to these abrupt events, indicating its sensitivity to climatic change.

Evidence for decadal-scale climatic fluctuations over the past two millennia has recently been revealed in southern Alaska. The climatic changes were more subtle than during the last



Results from the analysis of lake sediments from Baffin Island and Greenland and comparison with temperature reconstructions based on data from Greenland ice cores. The biogenic silica (a) measured from the cores reflects lake productivity and is positively related with summer temperatures (b). The amounts of planktonic diatoms (diatoms are microscopic algae that produce exoskeletons made of silica) relate to the persistence of ice cover on the lakes throughout the year (c). Changes in the diatom flora have been used to reconstruct temperature changes at Fog Lake, Baffin Island (d). The evidence indicates that warm conditions persisted during the early to mid-Holocene and that climate has become cooler and more variable during the past 4000 years. These variations permitted Norse settlement of Greenland during a warmer period, and forced abandonment when the climate cooled. Some lakes also show a pronounced increase in warmth during the twentieth century. (Reprinted from Quaternary Research *58, Kaplan et al., Holocene environmental variability in southern Greenland inferred from lake sediments, 149-159, 2002, with permission from Elsevier.)*



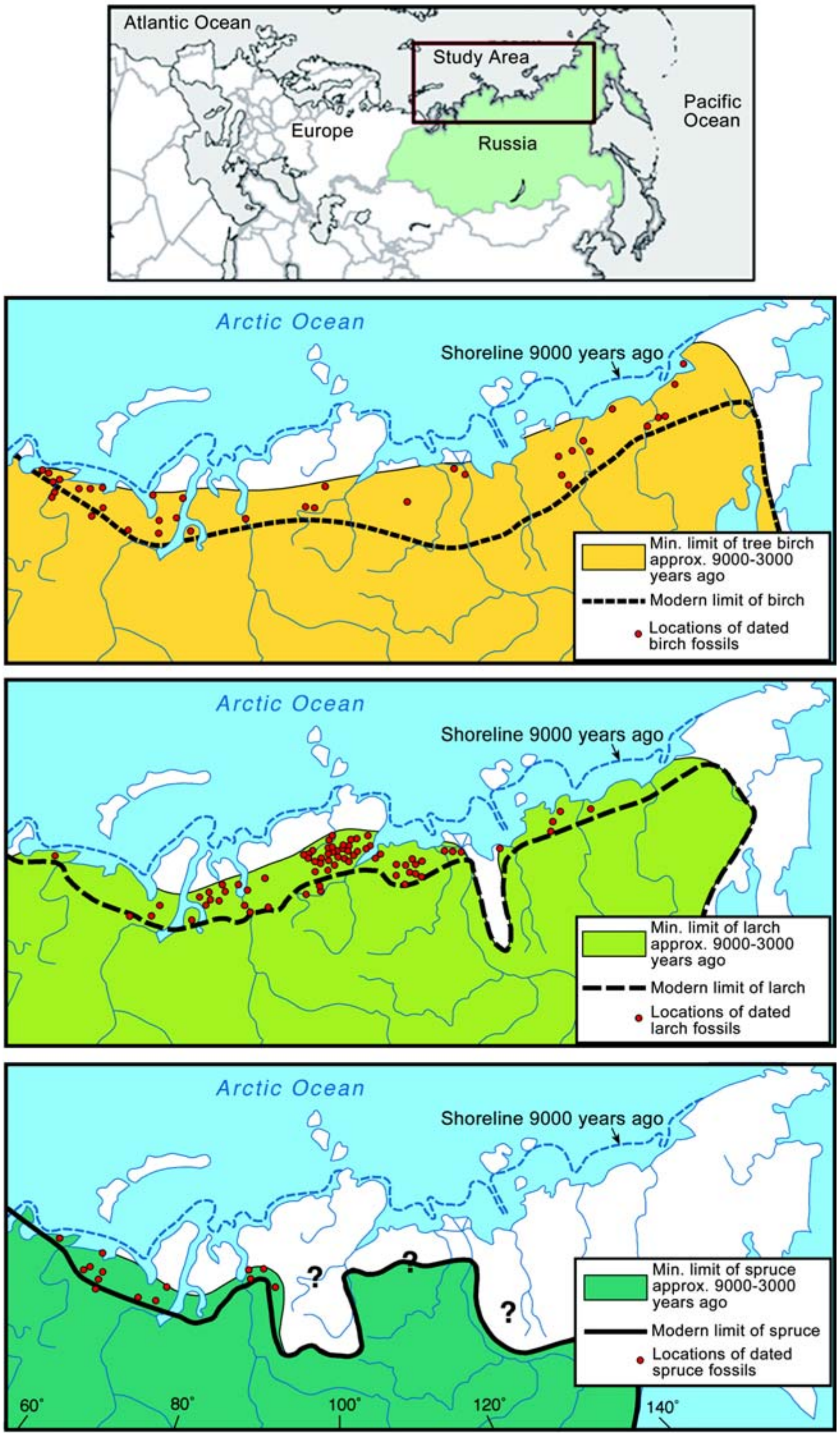
The effect of reducing the sea ice cover in a general circulation model. The map shows the amount of wintertime (December, January, February) warming caused by a 25% reduction in sea ice area during the winter, compared to the present-day extent of sea-ice. This reduction in sea-ice extent approximates the inferred middle-Holocene thermal maximum. This simulation shows warming of up to 5ºC concentrated over the northwest North Atlantic region. In contrast, the Pacific sector shows only a small response, despite equivalent reduction in sea ice in the North Atlantic. (Reprinted from Quaternary Science Reviews *22, Smith et al., Sensitivity of the Northern Hemisphere climate system to extreme changes in Holocene Arctic sea ice, 645-658, 2003, with permission from Elsevier.)*

interglacial–glacial transition; nonetheless, temperature fluctuations on the order of 1–2°C induced major changes in treeline vegetation, moisture balance, and glacial extent.

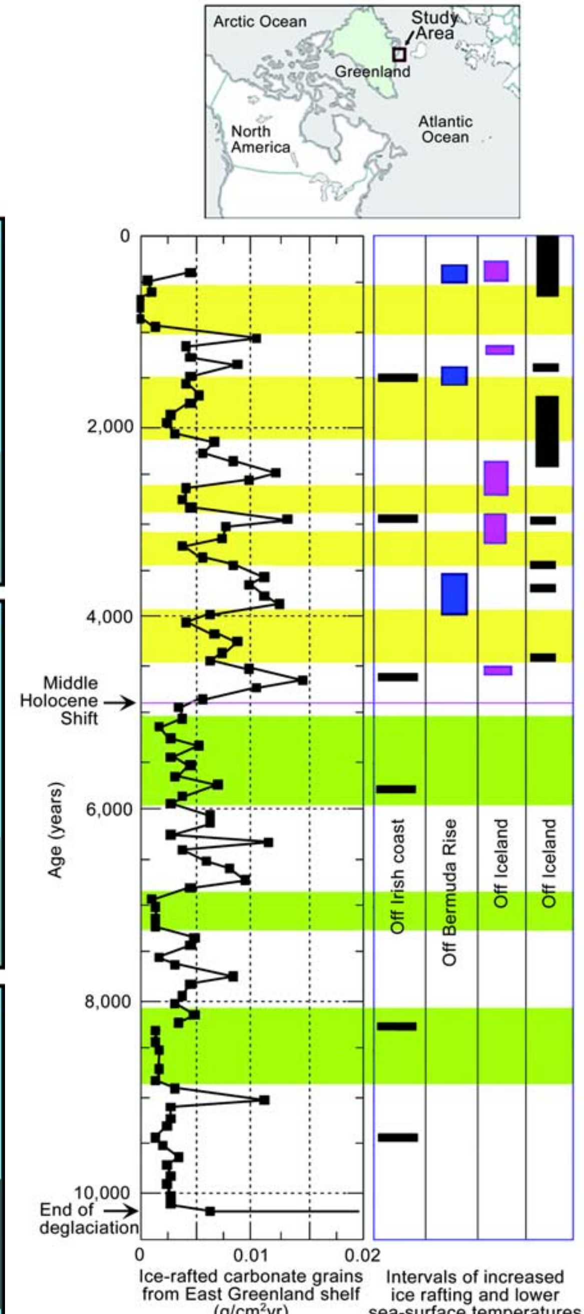
In eastern North America recent PARCS studies in the Baffin Island and southern Greenland region have provided key insights into both long-term climatic variability and the impact of such variability on the early Norse settlement and subsequent abandonment of Greenland. Sediment cores from a number of lakes have been studied for biogenic silica content, magnetic susceptibility, and diatom content to reconstruct past lake productivity and temperature. These records, which in some cases extend back over 9000 years, show that summers cooled by perhaps 2°C in the past 5000–2000 years. The lake sediment records compare well with paleotemperature estimates from the Greenland ice cores. This general cooling appears related to decreased summer insolation caused by natural changes in the earth's orbit. In addition, the last 2000 years are typified by increased climatic instability compared to previous millennia. Norse settlement in Greenland (approximately A.D. 985) coincided with an unusually warm interval within this period of climatic instability, while the abandonment (approximately A.D. 1350–1550) coincided largely with decreasing temperatures. Where temporal resolution is sufficient, the records depict considerable and rapid warming and related changes in the later twentieth century.

PARCS scientists have worked in close collaboration with researchers outside of North America to examine questions of past environmental change in all regions of the Arctic. Such international efforts are essential to understanding the Arctic as an integrated and coherent system from a circum-Arctic perspective. These efforts occur at a programmatic level, with PARCS participation in the IGBP's CircumArctic PaleoEnvironments (CAPE) program, and at a collaborative research level involving individual principal investigators from several countries. As part of this participation, PARCS was a major contributor to two recent CAPE meetings. The first, in 1997, addressed changes in Holocene climate around the Arctic by synthesizing paleoenvironmental conditions and comparing the results of these syntheses to climate model output (http://www.ngdc.noaa.gov/ paleo/cape/index.html). The second, in 2000, focused on sea ice and its role in the climate system. Over 50 researchers from 10 countries met in Iceland to review sea ice variability as reconstructed from the paleoenvironmental records and investigated in numerical models (http://www. ngdc.noaa.gov/paleo/cape/index.html). Sensitivity experiments were conducted for this meeting to evaluate the effect of sea ice extent on circum-Arctic temperature. By reducing the extent of sea ice from the present-day amount to an estimated minimum cover of the Holocene, the Atmospheric Global Climate Model at the National Center for Atmospheric Research (NCAR) showed warming effects concentrated in the North Atlantic region. Similarly, by increasing sea ice cover, the model simulated heightened effects in the North Atlantic.

Other examples of PARCS cooperative and integrative research with workers from the international community include collaborations with European colleagues on ocean circulation changes around the East Greenland/Iceland region, and reconstructions of northern treeline on the Eurasian continent. Stumps and other well-preserved remains of former trees from the Kola and Yamal Peninsulas of Russia collected by PARCS researchers have been combined with similar evidence collected by international and Russian research teams to reconstruct the postglacial history of the northern boreal forest treeline across



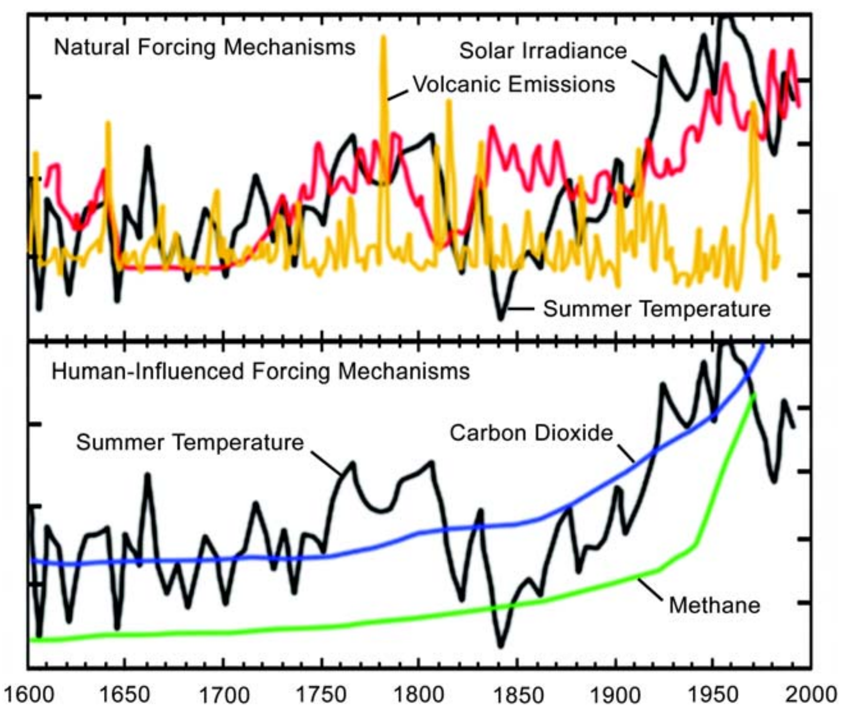
The collection of preserved stumps and other remains of trees from and beyond the modern treeline in northern Eurasia shows that the northern boreal forest extended as far north as the modern Arctic Ocean coastline between approximately 9000 and 3000 years ago and then retreated to its modern position. The initial development of the northern boreal forest and its northward expansion appears related to increased summer insolation and increased temperatures in the Nordic seas during the early to mid-Holocene. As insolation declined and the seas cooled, the treeline retreated. (Reprinted from Quaternary Research *53, MacDonald et al., Holocene treeline history and climate change across northern Eurasia, 302-311, 2000, with permission from Elsevier.)*



The flux of detrital carbonate measured in an ocean core from the East Greenland Shelf. The peaks in carbonate flux above the middle Holocene shift (white horizontal bars) are interpreted as sea-surface cooling episodes. These correspond with peaks in sea salt sodium and with lower sea-surface temperatures recorded in cores off Ireland, on the Bermuda rise, and off Iceland. Before the middle Holocene shift, intervals of low carbonate flux in the core correspond with intervals of elevated sea salt sodium, and the carbonate flux peaks do not correspond to coolings.

Eurasia. This study showed that the northern forest became established between 11,000 and 10,000 years ago across all of Eurasia except the Kola Peninsula, where it was delayed by about 1000 years. During the period 9000–3000 years ago the northern forest of Eurasia expanded significantly north of its modern position and reached as far as the present Arctic Ocean coastline in places. The retreat of the forest was synchronous across Eurasia, occurring at about 3000 years ago. The development and northward expansion of forest appears to be related to increasing summer insolation in the early Holocene due to natural variations in the earth's orbit and the warming of the Nordic seas. In addition, the changes in albedo (the reflection of solar radiation back into space from the earth) and heat transfer caused by the advance of the forest itself may have served as a positive feedback promoting the northward advance of trees. Decreasing insolation and ocean cooling generated the retreat of treeline in the later Holocene.

In the East Greenland/Iceland Shelf region of the North Atlantic Ocean, PARCS research has led to a greater understanding of ocean circulation dynamics during the past 5000 years. Marine and estuarine records from the region show that sea surface temperatures fluctuated with the amount of polar water present in the East Greenland Current during the past 4700 years. These temperature cycles correlate well with temperature fluctuations recorded in an ice core from Greenland and with cyclic changes in marine cores from the North Atlantic. Because the East Greenland Shelf is proximal to the source of polar water, it appears that these sites are more sensitive to changes and capture higher-frequency oscillations as well.



A circum-Arctic synthesis of summer temperature indicators from 29 records, including tree rings, lake and marine sediment cores, and ice cores, shows that the twentieth century has been characterized by an unusually prolonged period of high temperatures that appears unprecedented over the past 400 years. Some of the warming is likely related to natural variations in solar output and volcanic activity, but the magnitude and duration of the warming also suggests the impact of greenhouse gases on the Arctic climate.

One of PARCS' primary goals is to integrate paleoenvironmental records to provide comprehensive reconstruction and analysis of climatic change. To facilitate these syntheses and to provide a useful resource to the community, PARCS has developed an online "atlas" (http://www.ngdc.noaa.gov/paleo/parcs/atlas.html), which was initiated by the PALE program. The atlas displays the results of PARCS synthetic research and provides access to the primary data, the synthesized data, and the methods of synthesis. PARCS will continue to expand the atlas with the addition of data derived from its current two research foci. Another example of this approach from the PARCS community is the Alaska PaleoGlacial Atlas (http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/), which provides an accessible, geospatial database of present and former glacier extents across Alaska.

In another important synthesis and analysis effort, PARCS researchers collated paleoclimatic records of summer temperatures from a variety of sources, including tree rings, lake sediments, and ice cores, to produce a circum-Arctic record of climatic change for the past 400 years. This reconstruction provided clear evidence that the magnitude and duration of warming in the Arctic during the twentieth century was unprecedented over the past 400 years. The study also concluded that, although much of this warming could be explained by natural forces, such as variability in solar radiation and volcanic activity, a significant portion is due to the impact of anthropogenically increased greenhouse gas concentrations.

These few examples of PARCS research demonstrate the considerable substantive, methodological, temporal, and geographical scope of the program. Despite the broad range of research topics and field areas, three common themes arise, each related to understanding the Arctic system and its response to future global warming.

PARCS scientists Al Werner, Darrell Kaufman, and students recover a lake sediment core from a floating platform on Sunday Lake, southwestern Alaska.

First, the Arctic system undergoes significant climatic and environmental variability at time scales ranging from annual to millennial; attempts to understand the biological and physical systems of the Arctic must consider this background of variability. Second, many of the natural forces that drive climate variability—some of which we understand, some of which we are still unraveling—will continue to impact the Arctic in the future and, unless their causes, periodicities, and impacts are understood, will obfuscate the detection of anthropogenic changes and confound efforts to mitigate those changes. Finally, an increasing body of evidence from paleoclimatic records attests to the unusual warmth in the Arctic during the twentieth century that appears to be the product of increased greenhouse warming.

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Human Dimensions of the Arctic System

Interdisciplinary Approaches to the Dynamics of Social–Environment Relationships

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In 1997 the National Science Foundation Arctic System Science (ARCSS) program launched the Human Dimensions of the Arctic System (HARC) initiative. Its goal is to "understand the dynamics of linkages between human populations and the biological and physical environment of the Arctic, at scales ranging from local to global." Since its inception in 1989, ARCSS had focused on the physical and biological aspects of the Arctic system. The HARC initiative was intended to help expand the scope of ARCSS to include more work on the place of humans within that system. Taken together, HARC projects offer the most direct link between ARCSS research and society, providing relevant information on topics of importance to Arctic communities and the world at large.

HARC developed through projects proposed in response to the new initiative and through the incorporation of existing projects that had a clear focus on human dimensions. These projects had in common the involvement of several disciplines, innovative approaches to posing and studying research questions, and a foundation of prior collaboration or at least interaction among the researchers from various fields. In all of ARCSS, collaborative multi-investigator projects are the standard approach to addressing complex, systemic questions. The same is true of HARC, with the additional complication that the investigators come from several branches of science, not just the closely related disciplines in one area of study.

The projects carried out under HARC to date, some of which are described below, have helped the ARCSS program make considerable progress in its collective understanding of human dimensions topics and the methods and approaches best suited to their study. Nonetheless, the initiative has not attracted the quantity of proposals that was expected. There are several possible reasons, including the difficulty of assembling a large, multidisciplinary team while also establishing the necessary connections with those Arctic people who may be both subjects of and collaborators in the project. To try to generate more activity under HARC, and to provide a means by which current HARC investigators could interact and share ideas, NSF has funded a Science Management Office (SMO) for HARC since 2001, based on similar offices already set up for other ARCSS initiatives.

The SMO has held several online workshops, designed to spur creative interactions among researchers on HARC topics without the burden, cost, and size limitations of in-person workshops. The results of these workshops are available at the HARC web site (http://www.arcus.org/harc). To help turn some of the online ideas into actual proposals, the SMO received an incubation grant from NSF's Biocomplexity Program, which was used to bring prospective researchers together to discuss specific projects and the general challenges of HARC research. The SMO is also coordinating a special issue of the journal *Arctic* dedicated to human dimensions research. This issue is expected to be published in 2004.

In February 2002 the ARCSS program had an all-hands workshop to review progress and determine how the program should be restructured to build on what has been learned and to fill major gaps. One question was the place of HARC in the larger scheme of ARCSS. HARC had been seen either as an initiative pervading all aspects of ARCSS or as a largely separate venture with few tangible connections to the main thrust of ARCSS. Following the workshop, it has become clear that HARC is a critically important component of Arctic science and that a greater effort is needed to make explicit links between HARC and the other initiatives within ARCSS. As has been demonstrated many times throughout the ARCSS program, collaboration and integration among projects, crossing disciplines and themes, results in valuable achievements with greater relevance for society.

Examples of HARC Research

While the role of the SMO is important, the essence of HARC is in the projects. To date, these have been conceived separately by their research teams, without any larger effort to coordinate or direct the overall program. As noted above, links with other ARCSS initiatives are expected to become stronger in the near future, providing a degree of coordination that, ideally, will not interfere with the creativity and curiosity of potential HARC investigators. This section describes several HARC projects to give an idea of the scope of the initiative and the breadth of inquiry that has so far been undertaken.

Environment and Social Change in the North Atlantic Arc

Fishing communities are clearly linked to their environment, but the implications of those links, particularly when environmental conditions change, are sometimes far from obvious. Examining these links is the topic of a research project looking at four fisheries-dependent regions of the northern Atlantic: Newfoundland/Labrador, Greenland, Iceland, and Norway. The project integrates natural science (oceanography and biology) with both quantitative and qualitative social science. It has been supported in two stages, first by ARCSS, from 1996 to 2000, and then by the Arctic Social Science Program, from 2000 to 2003. (Although the ARCSS grant actually preceded the HARC initiative, this project addresses human dimensions issues and is therefore grouped with others funded specifically through HARC.)

The research team includes two social scientists and a biological oceanographer. By assembling and analyzing oceanographic, biological, fisheries, and socioeconomic databases at the finest practical scales, they have been able to document changes in social and environmental parameters, identify associations among those changes, and examine regional similarities and differences in adaptations. These findings have further allowed the development of an integrated environment–fisheries–employment model for policy research.

The study's results include:

- New analyses linking ocean–climate changes, marine ecology, fisheries, and the differential development of human communities in West Greenland;
- Analyses of how a fishery transformed its ecosystem, which transformed the fishery in turn, in northern Newfoundland;
- Comparative studies of the effects of fisheries crises on human populations in Norway, Iceland, Newfoundland, Greenland, and the Faroe Islands;
- Models of policy options and possible paths to recovery for a collapsed fishery off Newfoundland;
- Work examining how Arctic-origin salinity anomalies impacted two fishing communities of North Iceland; and
- A historical report on the development of fisheries in Greenland.

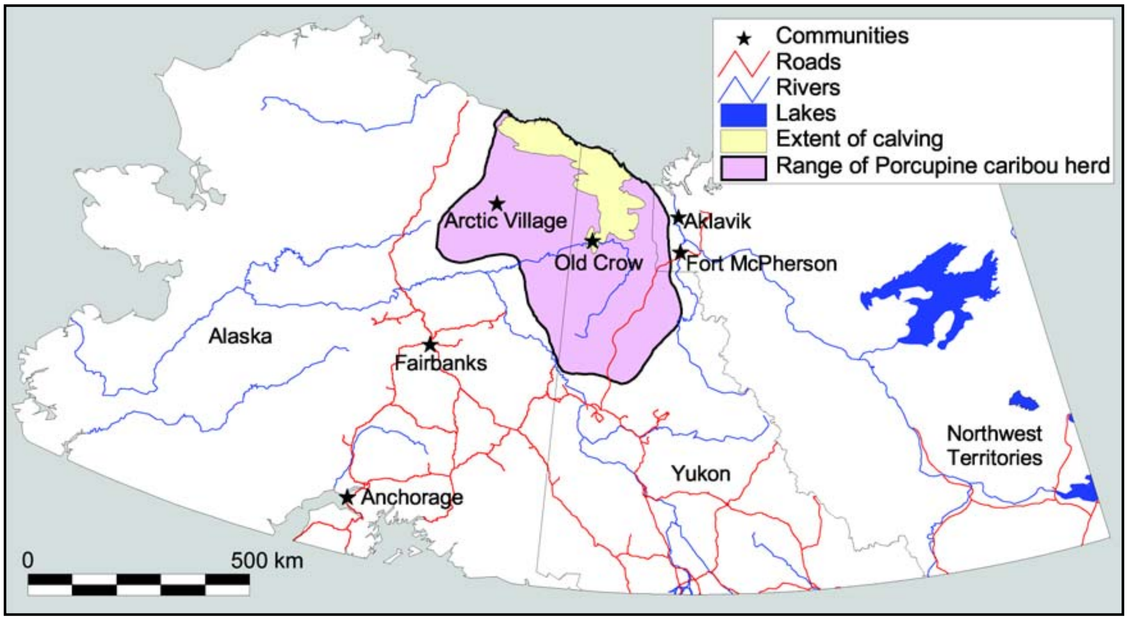
Further information and a complete list of references are available at the project web site (http://pubpages.unh.edu/~lch/naarchom.htm).

Sustainability of Arctic Communities

Beginning in 1996 the National Science Foundation supported an experiment in human dimensions research in the Arctic entitled Sustainability of Arctic Communities: Interactions Between Global Changes, Public Policies and Ecological Processes. (Like the previous project, the topic of this research clearly fits within HARC, although the project actually began before HARC was formally introduced and was jointly funded by ARCSS and the Methods and Models of Integrated Assessment Program.) Twenty-three researchers representing nine disciplines proposed to develop an integrated set of models responsive to policy-makers' questions about the ability of Arctic communities in the range of the Porcupine caribou herd to sustain themselves in the face of global climate change. They hypothesized that the effects of climate change cannot usefully be studied out of the context of resource development, tourism, and government spending in the Arctic.

What started as an interdisciplinary team of researchers became an interdisciplinary collaboration of researchers and local knowledge holders from five Arctic communities: Aklavik, Ft. McPherson, Old Crow, Kaktovik, and Arctic Village. The project's partner communities defined sustainability in terms of five community goals:

- Continued use of, and respect for, the land and animals;
- A cash economy that is compatible with their relationship with the land and animals;
- Local control and responsibility for their homelands and resources;
- Education of young people in the twin areas of traditional knowledge and western science,



Range of the Porcupine caribou herd and its calving area.

and education of the outside world about community goals and ways of living; and

- A thriving culture that has a strong, clear identity, that is based on language and time on the land, and that honors and respects elders.

Drawing on local knowledge and 20 years of empirical research, the project developed a hierarchy of computer models intended to serve as a basis for discussion about alternative futures. Subsystem models (developed or refined in this project) simulated changes in vegetation; caribou population and energetics; employment, hunting, and migration; and resource-development-related effects on caribou. Based on sensitivity testing of these models over the range of scenarios being considered, the research team integrated simplified subsystem representations in a spreadsheet-based synthesis model. They incorporated the results of repeated simulations using the synthesis model in a web-based interactive Possible Futures Model. This model incorporates plain English explanations for modeling results and a feedback feature so that model users can help identify what may be missing or wrong.

What has been learned so far? When the probability of warm summers, deep snows, high insect harassment, and high harvests were kept constant, chance occurrences of a sequence of "bad" years set in motion a large caribou population decline. In other runs an absence of such strings of bad years produces a large population increase. Even without global warming, then, over any given 40-year period, the chances of a decline in the caribou population are significant. The research team had hypothesized that, integrating the effects of summer forage, winter snow depth, and insect harassment, global warming would increase the probability of a herd increase. Repeated simulations suggest the opposite: the effects of periods of high insect harassment and more frequent winters with deep snows appear to outweigh the effects of better summer forage. Though the project's community partners thought that these results do not take into account important variations within the region, all agreed that the simulations help to advance our understanding and identify knowledge gaps.

The research team compared the likelihood that the Porcupine caribou herd would show a decline over 40 years based on four oil development scenarios in which concentrations of cows and calves avoid progressively larger parts of the coastal plain during a three-week period in June. The team developed scenarios based on a new assessment of oil potential prepared by the U.S. Geological Survey coupled with an assessment of changing worldwide petroleum markets. They evaluated the relationship between development-related displacement and a change in calf survival. There was a significant inverse relationship between displacement distance and calf survival.

Based on modeled relationships, the most likely decline in the Porcupine caribou herd because of global warming does not appear to be accompanied by an increase in the number of years of poor hunting. A principal reason for this finding is that communities organize collective hunts when hunters are not able to meet their needs through individual and small group hunts, thus delaying years of poor hunting. This is a good example of how local knowledge can improve on the "linear thinking" so often imposed by using one model equation throughout the entire range of possible conditions. Modeling also confirmed the importance of sharing in mitigating effects of uncertainty brought about by variations in caribou migration patterns and job availability.

More important than any particular simulation result is what was learned about the feasibility of focusing such a broad range of disciplines and knowledge systems on a common research problem. It is possible to explicitly define dimensions of sustainability, to develop explicit scenarios for consideration, and to represent relationships that cross disciplines in a common modeling framework. It is also possible to focus on the "whys" rather than on what are inevitably highly uncertain projections of the future.

The Sustainability of Arctic Communities project is continuing under a second NSF grant. This phase of the project focuses on areas of key uncertainty, including:

- Climate and development effects on whaling for bowhead and beluga;
- Harvest and non-summer forage-related effects on the Porcupine caribou herd;
- Local management of resource development effects;
- Extension of modeling to other North American caribou herds, focusing on the relative importance of calving grounds; and
- Extension of modeling of a single community (Old Crow) to all communities in the Porcupine caribou region.

Further information, including the Possible Futures Model, is available at the project web site (http://www.taiga.net/sustain).

Reindeer Herding in Transition

Significant change has occurred in reindeer herding in the Seward Peninsula, Alaska, because of the migration of large numbers of the western Arctic caribou herd onto the peninsula in winter. Examining these changes, their relation to social and economic changes, and their environmental and socio-economic implications is the topic of an interdisciplinary project that began in 1999. The project is identifying climate factors that influence herding practices, the role of reindeer herding in local economies, the ecological impacts of caribou grazing, and the socio-economic consequences of losses of reindeer. To do so, it has five components:

- Socio-cultural studies, including interviews with reindeer herders;
- Data collection and survey sampling for the economic analyses;
- Installation of satellite-linked remote weather stations for climate monitoring;
- Set-up of experimental sites for vegetation studies; and
- Deployment of radio and satellite collars to monitor animal movements.

The interviews examine not only the social and economic aspects of herding, but also oral histories concerning traditional ecological knowledge of reindeer–environment interactions over the century that reindeer have been herded in the region. As part of the project's outreach efforts, excerpts from these interviews will be used in thematic radio shows addressing historical and present-day issues concerning reindeer herding in Alaska. Reindeer herding is an important part of the region's culture as well as its economy, and impacts to herding have substantial implications for identity as well as employment.

An economic model of reindeer herding is being developed to examine the role of reindeer herding in the economy of the Seward Peninsula. There are two products from reindeer herding: meat and velvet antler. The price of velvet antler has fluctuated greatly in the past decade, and the losses of reindeer from the influx of caribou has reduced harvests to the point that meat sales now generate more revenue than antler sales.

Seward Peninsula reindeer herders' cost of operation.

Goods and Services	Cost/Year ($)
Air charters and shipping	14,650
Snowmachines/ATVs	10,500
Vehicle repair services	1,725
Fuel and oil	3,500
Food for handlings	2,000
Handling/butchering supplies	2,000
Corral maintenance	1,575
Veterinarian instruments, drugs, ear tags	1,750
Recordkeeping, leases, credit	1,500
Miscellaneous supplies and services	460
Labor	2,500
Total annual cost estimate per herd	42,160
All herds*	590,240

* The total annual cost estimate for all Seward Peninsula reindeer operations is obtained by multiplying the total per herd cost estimate by 14 herds.

The last three components examine climate and ecological impacts of caribou. Weather stations have been set up, satellite collars have been placed on both caribou and reindeer, and vegetation plots have been set up for experimentation. Studies of the foraging ecology of caribou and reindeer have shown the potential for competition during winter months. One offshoot of the telemetry exercise is the transfer of technology to reindeer herders. The project team held a workshop to introduce satellite telemetry, GIS, and Internet technologies to reindeer herders as a management tool. The extensive participation of the herders in the project is both critical to the research itself and an excellent means of ensuring that the methods and results of the project can be applied where possible to the benefit of the herders.

The Barrow Symposium on Sea Ice

Subsistence whalers on Alaska's North Slope depend on their knowledge of sea ice to travel, camp, and hunt safely and effectively. Sea ice scientists probe the same ice through microscopes, bore holes, and remote sensing. How can these complementary forms of knowledge be shared so that both groups can help inform the others' knowledge? This was the challenge of the Barrow Symposium on Sea Ice, held in Barrow in October and November 2000.

To prepare for the symposium, researchers and community members selected five case studies spread over more than four decades. Each case study was described in detail, a process involving meteorology, oral history, oceanography, traditional knowledge, sea ice physics, and other disciplines to draw on the various sources available and to capture the many aspects not only of the ice but also of the ways that hunters and others use and understand the ice. For this reason the research team was large and diverse, with a strong emphasis on community involvement from the beginning.

Additional researchers and community members took part in the symposium itself, which resulted in three days of highly interactive discussions about the five case studies. The dynamics of ice movement were of particular interest, especially the process of spring breakup. In 1957 a catastrophic shattering of sea ice left whalers scrambling for shore, having abandoned their whaling gear on the ice. An analysis of the weather events at the time showed that although the particular conditions were not common, they had occurred several other times in the past eight decades for which weather records are available. The role of wind, storm surges, and ice formation were examined, with one elder pointing out that the ice that spring was regarded as suspect because it contained a very high proportion of fragile multi-year ice, which unlike first-year ice is more likely to shatter than deform. This collaborative reconstruction gave a much more complete view of the event than would have been possible from a single source.

The role of technology in studying ice and forecasting ice conditions was another topic of great interest to whalers and scientists alike. Reliance on global-positioning satellite systems and the availability of advanced search-and-rescue capabilities such as helicopters may be leading whaling crews to take more risks on the spring ice. In recent years, hunters have occasionally been carried out to sea when the shorefast ice breaks free, requiring a rescue operation. To date, no lives have been lost, but there is naturally considerable concern about safety. Providing remote sensing imagery to the whalers, and getting their help in ground-truthing the images, is one option in helping avoid surprises during whaling. At the same time, decreasing the whalers' reliance on traditional knowledge may erode the social standing of elders whose experience and expertise was previously essential, and it may lead to increased risk by lowering the attentiveness of whalers to important clues in the ice around them. These social factors are an important consideration in our understanding of the relationship of hunters and sea ice.

The Kola Peninsula Project

The Kola Peninsula is one of the most populated and polluted regions in the Arctic. The American Association for the Advancement of Science's Program on Europe and Central Asia, the Institute for Ecological Economics at the University of Maryland, and the Kola Science Center in Apatity, Russia, are in the first phase of a multiyear U.S.–Russian research effort to increase understanding of the role of human dynamics on ecosystem functions and explore development strategies to enhance ecosystem health, ecological sustainability, and economic diversity. The project initially focuses on the Imandra Lake watershed and then will examine the Kola and Tuloma River watersheds. All of these watersheds cut through the heart of the industrially developed ecosystems of the Kola Peninsula and account for the release of major pollutants into the Barents and White

Seas and the Arctic Ocean.

Four research questions are being examined:

- What effect has the post-Soviet decrease in industrial and human activity had on the ecological health or resilience of the watershed?
- What future models of economic and social development in the region can increase economic productivity while not degrading the health of the watershed?
- How can integrated modeling be used as a consensus-building tool for making decisions about further economic and social development of the region?
- What are the possible scenarios for future development of the region under changing global conditions, such as global warming?

Using a watershed as the unit of analysis, the project will:

- Describe each watershed's terrestrial and aquatic biogeochemical cycles and their changes over the past 65 years;
- Develop a working model of each watershed; and
- Involve local stakeholders through the model development, testing, and implementation phases.

The Imandra Lake watershed and the Kola and Tuloma River watersheds were selected because they provide diverse mixes of human land use, as well as serious environmental degradation through numerous causes. This interdisciplinary project combines natural systems research and social science research. The result will be a better understanding of site-specific contributions to large-scale models of the Arctic systems functions and threats. To date, the project has developed a model for Lake Imandra, charting the concentrations of certain contaminants over time as development activities change, and has held stakeholder meetings in several communities. The willingness of community members to speak openly appears to vary widely, largely as a result of different economic and social relationships between residents and industry. More information is available at the project web site (http://www.aaas.org/international/eca/kola/).

Landscapes and Seascapes in the North Atlantic

Iceland is particularly vulnerable to environmental changes, including the impacts of both climate and volcanism. Iceland's vulnerability to climate impacts in the past, and potentially in the future, is due in large measure to the variability of the climate. The project called Landscapes and Seascapes: Linkages between Marine and Terrestrial Environments and Human Population in the North Atlantic may be seen in the context of current concerns regarding potential future global and Arctic changes, the crisis in the world's fisheries, and concerns regarding land use and continuing erosion of land surfaces in Iceland. The research focus is threefold:

- A number of specific climatological and environmental questions related to the documentation of twentieth-century changes and the assessment of potential future changes relative to the recent past;
- Assessment of the impacts of these environmental factors on a specific society (Iceland) in the context of other socio-economic pressures; and
- Actual and potential human adaptations to these impacts and the implications of such adaptive strategies for sustainable development.

To provide data with which to assess the impact of future environmental changes on Icelandic society, the project team is also reviewing and synthesizing results from recent coupled Ocean/Atmosphere General Circulation Models (O/AGCMs) to answer several questions:

- What are the predicted changes in precipitation and temperature in Iceland over the next 10–100 years?
- What are the corresponding predicted changes in sea surface temperatures around Iceland?
- What are the predicted variations in the East Greenland sea ice over the next 10–100 years?
- What are the predicted variations in ocean currents around Iceland in 10–100 years?

The project includes two specific case studies, one conducted in the Myvatn area of northern Iceland, which is focused mainly on a farming and land-use economy, and the other in southern Iceland (the Westman Islands), which is focused mainly on a fisheries-based economy. The case studies will address some of the local and regional implications of environmental variations and changes. Specifically, researchers have been asking farmers and fishers how they have adapted and/or responded to certain climatological and environmental events in the recent past, as well as how they might adapt and/or respond to climatological and environmental scenarios that are predicted in the near future. The team has been particularly impressed by the wealth of local knowledge found among both farmers and boat skippers who have been interviewed. The information gathered in this manner will yield much insight into sustainable development in Arctic and sub-Arctic regions in the future.

A strong research team, based in the U.S. and in Iceland, includes both social scientists and natural scientists with backgrounds in fisheries, anthropology of fishing communities, climatology, and human ecology. This diversity of backgrounds allows the team to analyze and interpret records of climate, agriculture, fisheries, the knowledge of farmers and fishermen, and other indications of climate variation and its impacts on the Icelandic economy, society, and culture. Some specific research questions addressing the documentation of twentieth century changes include:

- How have precipitation and temperature patterns in Iceland varied?
- How have sea surface temperatures in the vicinity of Iceland varied?
- How has the East Greenland sea ice varied?
- What changes in ocean currents around Iceland can be established?
- What are current annual yields of grass per hectare in Iceland?
- How many sheep, cattle, and horses are currently kept in different parts of Iceland?
- Given the problems with erosion in Iceland, how do farmers justify the numbers of livestock kept?
- What are the annual fisheries catches in Icelandic waters (specifically cod and herring) and what factors influence these catches?

Climate Variability and Change on the Alaskan North Slope

The purpose of this project—An Integrated Assessment of Climate Variability and Change in the Alaskan North Slope Coastal Region—is to help the community of Barrow, Alaska, adapt to climate variability and change by integrating scientific research in various disciplines into policy alternatives that address the community's primary concerns. It employs a wide range of methods, which were chosen based on specific community concerns highlighted in initial exploratory meetings between members of the research team and Barrow residents. Coastal erosion and flooding were identified as the most important topics to the community, and the eventual research team was assembled with that in mind.

The basic approach is to make a map of past events and responses and then to use this to construct a picture of future vulnerabilities and the potential for policy development. Hence, the project has or will:

- Characterize the impact of climate variability on the physical processes that cause extreme flooding and erosion events;
- Investigate these processes to understand the important mechanisms at work;
- Document past extreme flooding and erosion events and the community responses to them;
- Use physical and statistical models to try out "what if" scenarios concerning climate and environmental changes and community-suggested solutions;
- Assess the state of climate modeling specific for the Barrow area; and
- Examine the range of, and controls on, future climate scenarios for the region.

For this study to succeed, it is essential to understand residents' perspectives on climate variability and change in order to focus the scientific research on their principal concerns and eventually to advise them on possible policy responses to priority problems. An active partnership is possible because residents continue to be concerned about issues of climate change and variability on the North Slope. The research team has begun to construct this partnership through a series of public seminars, meetings with a variety of local citizens and groups, and discussions with local schoolteachers and students.

This project requires a breadth and depth of expertise, reflected in the participation of eight principal investigators from the fields of atmospheric sciences, anthropology, geology, political science, sea ice physics, and climate impacts. Nine other scientists are involved in the project, plus seven students. To make sure the group functions as a team, everybody on the project has a responsibility to interact with stakeholders as much as possible, and anyone can come along on the trips to Barrow.

Although it is too early to anticipate key results, research so far has turned up several interesting findings:

- Cyclone frequency and intensity over the Arctic as a whole have increased in the past 50 years, but, surprisingly, in the region affecting Barrow (the Beaufort–Chukchi sector), the only increase has been in summer cyclone intensity. On the other hand, average winds at Barrow do show a significant

increase, especially in winter. Dramatically apparent in the wind-event record is a relatively quiet period from the late 1960s to the early 1980s, a period during which Barrow grew greatly.
- The variations in atmospheric circulation in this sector are not significantly correlated with the Arctic Oscillation, although the Pacific North American (PNA) teleconnection pattern index does show a link to some variables. This is important if there is going to be any chance of linking future large-scale climate scenarios to changes of local importance.
- North Slope residents clearly perceive that the climate of the region has changed in living memory. Factors influencing this perception include the fact that auguring for foundations in Barrow has had to go deeper to reach permafrost, snowmelt onset at hunting camps is becoming unpredictable, the sun is feeling hotter, and the summer mosquito population is increasing. Careful examination of the climate records at Barrow generally supports these perceptions.
- The Beaufort–Chukchi cyclones of October 1963 and August 2000 produced the highest winds ever recorded in Barrow. The October 1963 storm caused significant flooding, contaminated drinking water, and interrupted power supplies. The August 2000 storm caused the wreck of a six-million-dollar dredge and removed roofs from 40 buildings. From the characteristics of the two storms, researchers concluded that the observed retreat in the western Arctic ice cover is unlikely to be an important contributor to increasing cyclonic activity in the future, although it may contribute to increases in storm surge and wave damage when storms do occur.

Further work is now being done to evaluate erosion mitigation strategies suggested by Barrow residents, as part of the continuing interaction of researchers and community members that characterizes this project. More information is available at the project web site (http://nome.Colorado.edu/HARC).

Future Directions

HARC's future will build on this record of research while linking more closely with other initiatives within ARCSS and with related activities elsewhere. This section describes some of those other activities and how they relate to HARC.

Arctic-CHAMP

One of the new ARCSS initiatives is the Pan-Arctic Community-Wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP), which seeks to understand the hydrological cycle in the Arctic. Part of that effort consists of examining the human role in relation to hydrology, including both human influences on the cycle and the impacts that changes in hydrology may have for people. There are several examples of such influences and impacts. People can affect the hydrological cycle in several ways, including controlling or changing runoff and river flow patterns through dams and changes in land use. Conversely the flow of water through the Arctic environment is critical to society in many ways, including drinking water, erosion, travel and transport, construction on permafrost, and impacts to the fish and wildlife that people depend on.

Studying the links between people and the hydrological cycle poses a typically HARC-like challenge. There are considerable gaps and uncertainties in our understanding of many aspects of Arctic hydrology, especially in terms of feedbacks and links among the various processes by which water circulates through the environment. An online workshop on Humans and Hydrology, organized by the HARC SMO, identified several important topics and ripe questions for research. These include ways to incorporate environmental change into community planning, the vulnerability of Arctic communities with specific reference to waste disposal practices, the degree to which infrastructure engineering standards are likely to accommodate permafrost warming, and the characterization of human–hydrology interactions on a variety of scales to identify geographic and other patterns of significance. Research on the human dimensions of the hydrological cycle should help make such topics an integral part of Arctic-CHAMP.

Land–Shelf Interactions

The Land–Shelf Interactions (LSI) initiative is an outgrowth of efforts within the Russian–American Initiative for Shelf–Land Environments in the Arctic (RAISE) project umbrella, which supports U.S.–Russian bilateral research on environmental change in the Russian Arctic. Because of the substantial influence of the Eurasian landmass on Arctic runoff, climate, sea ice formation, water mass formation, and other processes that impact environmental responses to change, the

Arctic cannot be properly understood in a systemic manner without coordinated, interdisciplinary efforts in the Russian Arctic. However, many aspects of environmental change at the Arctic land–sea boundary can also be appropriately studied outside of Russia, so this science planning effort is generic, rather than geographically delimited, and will include research efforts in Alaska and other portions of the Arctic.

The overall objective of the current science planning effort is to lay the groundwork for a coordinated, interdisciplinary research opportunity in the Arctic that would focus on the coastal zone and would support land-, river-, and sea-based researchers who would take advantage of coordinated logistical capabilities that would otherwise be unavailable. LSI will be specifically centered on these research problems at the land–sea margin in the Arctic by focusing on the scientific challenges of environmental change in human and biological communities and related physical and chemical systems. Another important focus should be on the role of food chains and the efficiency of transfers of carbon, nitrogen, contaminants, and other constituents from the environment, through marine and terrestrial organisms, to local communities. Because of the relatively high density of human communities in Arctic coastal zones, these foci provide an opportunity to address the linkages between marine and terrestrial ecosystems in ways that have direct relevance to society. This initiative could also examine the role of people in the Arctic system as an important mediator of interactions between marine and terrestrial food webs, which in turn affect the productivity of these systems. It is also worth noting that many uncertainties concerning environmental change in the Arctic can be approached through the study of past changes in biological communities in response to environmental change, including the responses of human communities.

As a result, study of the human dimensions of environmental change will be an important component of the overall LSI research program because of the heavy dependence of local Arctic communities on marine and terrestrial resources. The nearshore area is vital for many Arctic residents. Coastal communities depend on access to the sea and sea ice but are vulnerable to flooding and erosion. Significant subsistence activities take place in the nearshore area. The interactions among terrestrial, freshwater, and marine systems govern the boundary conditions associated with the nearshore as well as feedbacks on each of those systems. These interactions have a human element, too, as people affect the nearshore and are in turn affected by it. To involve natural scientists, social scientists, and Arctic residents in a discussion of this topic, one of the HARC online workshops was dedicated to this topic. (Transcripts and the workshop report can be found at the HARC web site). Among the topics that were touched on by workshop participants were the relationship of environmental change to community planning, human impacts on ecosystem health, environmental vulnerabilities, and past responses to environmental change.

In particular, it was recognized that changes in oceanographic features such as the presence of sea ice and the extent of nearshore brackish water may have significant impacts on the productivity and biodiversity of nearshore areas. From a physical standpoint, biological recovery to disturbance and biogeochemical cycles in general are slow at high latitudes. Human activities, too, may have an impact in this zone, such as through the outflow of municipal waste. It is also important to recognize that humans have modified the nearshore environment for thousands of years, and the changing role of people within the ecosystem needs to be taken into account. The effects of environmental changes on humans depend greatly on the impacts to species that are hunted or fished or to access routes across sea ice or through nearshore waters and river mouths.

The contributions made by participants in the HARC workshop have been incorporated into a more general science plan that is guiding LSI project development. Additional workshops and an implementation plan are likely prior to the initiation of any field research.

More information, including the current draft of the science plan, is available at the LSI website (http://arctic.bio.utk.edu/#raise).

SEARCH

A larger effort to examine environmental change in the Arctic is the Study of Environmental Arctic Change, or SEARCH, a multi-agency, coordinated effort to study variability and change in atmospheric, marine, and terrestrial systems that may be related to the polar vortex. The model for SEARCH is the program of research on the El Niño–Southern Oscillation (ENSO). ENSO-related research has tried to improve understanding of how changes in the environment important to people (such as fisheries, agriculture, and storms) may be related to ENSO variability. ENSO observations and research have even supported alerts of probable El Niño events, thereby helping regions to anticipate the need for economic adjustments, disaster relief, and the like.

SEARCH science planning envisions three panels to focus research efforts: Detecting Change, Understanding Change, and Responding to Change. The Detecting Change panel focuses on compiling a systematic database of long-term observations to detect and monitor Arctic environmental change. A key research question concerns the ability to detect conditions producing regime shifts. Small changes in one part of the environment may, under some conditions, produce a dramatic, non-linear change in another part (for example, ocean circulation affecting marine species composition).

Historical and archeological studies can play an important role in developing a long-term database of pan-Arctic environmental change. Relevant historical studies might include identifying and analyzing long-term records of human activities such as fishing and transportation, as well as compiling oral histories of environmental change. Coastal archeological sites contain shell middens and faunal remains whose chemical signatures can provide evidence of past climate variation. Comparing the presence or absence of human use at diverse terrestrial sites across the Arctic may also suggest Arctic-wide changes contained in patterns of regional or local changes.

The Understanding Change component of SEARCH consists of modeling studies to test ideas about links among different components of atmospheric, marine, and terrestrial systems, as well as process studies to understand potentially important feedbacks. Modeling studies may start by analyzing covariation in diverse but hypothetically linked data series (for example, the AO index, precipitation, poleward heat flux, indicators of ecosystem change, and social and economic factors), and the development of explanations for this covariability. For example, one approach might be to construct models of human activity and environmental connections based on re-analysis of paleo- and historical data.

Constructing a comprehensive Arctic system model will likely require different approaches to accommodate diverse space and time scales relevant to the atmosphere, marine and terrestrial systems, and social systems. While useful models already exist for aspects of the physical systems, ecological and social models only exist for a few regions of the Arctic. System-wide modeling may need to start with simplistic ecological and social models extrapolated from small regions. Nevertheless, SEARCH's comprehensive approach provides a significant new opportunity to characterize links and vulnerabilities of interconnected Arctic human and natural systems.

Certain critical feedbacks within the Arctic systems may attract more detailed attention from modelers. The freshwater balance provides one such feedback (see CHAMP above). Human activities may cause large-scale changes in land cover (such as fire control, grazing, and expansion of agriculture) or trace gas and particulate emissions that may, for example, affect albedo and moisture fluxes at the land surface. Changes in marine food webs from fish harvesting and aquaculture may interact with thermohaline changes and biogeochemical cycling. Social scientists may be interested in modeling interactions between global and Arctic social and environmental change: for example, how Arctic environmental changes affect environments and societies at lower latitudes, and how lower-latitude environmental, economic, and social changes affect Arctic ecosystems and societies. Archeological data can again play a role in testing the models' simulated responses against the paleoenvironmental record.

The Responding to Change component addresses the impact of the physical changes on ecosystems and societies, distinguishing between climate-related changes and those caused by other factors, such as resource utilization, pollution, economic development, and population growth. Of particular interest is the question of whether threshold phenomena exist in human–environment interaction, for example, how Arctic communities are adapted to normal ecological variation, and under what circumstances extreme environmental changes might cross a threshold to trigger social changes. Archeological and historical records may be useful in documenting and analyzing past large shifts in human activity and potential connections to environmental change.

SEARCH envisions developing a systematic method of connecting scientists with northern communities. It calls for establishing science–community communication networks in which researchers share data and findings with local governments and citizens and receive regular feedback on issues of concern. Structured community-driven monitoring programs can contribute to the Understanding Change component of SEARCH by providing early signals of change undetected by remote sensing methods, as well as by detecting environmental changes that are important to the communities and industries. Arctic residents could also participate through these networks in the Understanding Change component by reviewing model predictions for ecosystem change and suggesting new hypotheses and explanations of observed and predicted change.

The SEARCH study plan distinguishes between near-term activities and more distant goals for each of the three study areas. More distant goals include developing a modeling capability that moves toward prediction of future changes. Ideally, linked physical system, ecosystem, and social models (terrestrial and marine) of Arctic environmental change will address relationships between local changes and system-wide changes at sufficient temporal and spatial detail to make credible predictions of key variables at the regional and community level.

More information about the program as a whole is available at the SEARCH web site (http://psc.apl.washington.edu/search/index.html).

Conclusions

Research on the human dimensions of the Arctic system, similar to research on human dimensions of global change generally, is a challenging topic, laced with uncertainty, requiring creative and innovative approaches to come to terms with the dynamic links between social and natural systems, each of which is dynamic in itself. Typically social sciences research regards the natural environment as essentially static or at least variable in relatively simple ways, so that the complexity of the social setting can be examined without addressing complexity in the natural environment. Most natural sciences research does the opposite, treating human inputs and extractions in simple fashion so that the focus on the study can remain on natural complexity. Human dimensions research is the connection between these modes of studying complexity, and one major challenge is avoiding the conclusion that it is too complex to make sense of at all. Instead, as the previous sections indicate, HARC provides an opportunity to try new ideas, to work collaboratively with those who might otherwise have been only the subjects of research, and to understand how Arctic system and global change research can help society.

This last point is easy to overlook or discount. The test of basic research should not be a direct link to societal benefits, and the scientific justification for programs like ARCSS is well established. The role of HARC is not to justify ARCSS, nor to explain it to the public, nor to try to reshape ARCSS. Instead, HARC can help ensure that the results and lessons of ARCSS research—including HARC projects—assist Arctic communities and the global society address the implications of Arctic and global change. How, exactly, are people in the Arctic affected by their environment and the ways in which it changes? How, exactly, do social processes influence that relationship? What, exactly, are the ways in which people use information from ARCSS and elsewhere to plan for or adapt to anticipated environmental and social changes? Researchers are often reluctant to draw firm conclusions, citing continued uncertainty and the need for further observation and study. Such prudence is creditable, but when decisions are being made today, society must accept uncertainty and try to accommodate it as well as possible. As we better understand the role of humans in the Arctic system, we will better understand how even an imperfect understanding can be a tremendous asset to those faced with the uncertainties of the future.

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Integrated Data Management for ARCSS Projects

JOSS Breaks the Ice on Field Data Archival and Exchange

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The University Corporation for Atmospheric Research (UCAR) Joint Office for Science Support (JOSS) provides scientific, technical, and administrative support to the scientific community in planning, organizing, and implementing research programs associated with field projects worldwide. The National Science Foundation and the National Oceanic and Atmospheric Administration are its principal sponsors.

Access to and integration of multidisciplinary data from field projects recently completed or underway is critical to the timely and accurate understanding of the rapid changes that are now occurring in the Arctic. The NSF Arctic System Science (ARCSS) program is committed to facilitating data archival and providing easy mechanisms for data exchange among researchers interested in the Arctic system. JOSS offers some specific capabilities that address these two important ARCSS objectives.

JOSS has been involved in data management support for a number of ARCSS field projects, both domestic and international, including the Surface Heat Budget of the Arctic Ocean (SHEBA), Arctic Transitions in the Land–Atmosphere System (ATLAS), the International Tundra Experiment (ITEX), the Western Arctic Shelf–Basin Interactions (SBI) project, and the Arctic Regional Climate Modeling Intercomparison Project (ARCMIP). JOSS also participates on committees to further improve the collection, archival, and dissemination of all manner of Arctic data sets.

This paper discusses the organization of JOSS in the context of field project support and related data management activities, describes data management strategies that have been successfully implemented in ARCSS projects, provides some examples of specific support to projects, and discusses some of what the future holds for data management support to ARCSS field research.

Overview of JOSS Support Services

JOSS has a staff of skilled and experienced scientific, technical, and administrative specialists who collaborate extensively with geophysical scientists and organizations to assist them in planning, organizing, and conducting research by supporting scientific planning efforts, collaborative research programs, field experiments, and data management. Collectively the JOSS staff has decades of experience at these tasks, and the office has supported programs of all sizes worldwide for more than 20 years. JOSS adds value to the scientific endeavor through an integrated approach to the full life of projects (science, technology, data management, logistics, and administration).

JOSS Data Services

JOSS has worked for over 15 years to develop its data management support capabilities, which have contributed to the success of research projects in many locations and disciplines. Services include collecting complete, high-resolution, high-quality data sets, supporting project objectives, and providing tools to view these data during both the field and analysis phases of a project. One such tool is the JOSS field catalog, which has proven particularly useful for distributing preliminary data sets in the field, providing access to data products needed for operational decision making, and maintaining a running assessment of project accomplishments.

JOSS has developed and maintains a state-of-the-art data archive and dissemination system that provides single-source access to complete project data sets. Most data are accessible for browsing and ordering online, with connectivity to distributed archives. Early versions of data sets can be shared with limited access (under password protection) to expedite the timely exchange and integration of related measurements. Data are delivered at no charge over the Internet or via CD-ROMs or other media.

Capabilities are available to provide value-added data processing and quality control procedures to ensure the best possible research-quality data sets. A range of data processing, quality control, and documentation procedures is available, including format conversions, automated and visual data consistency checks, confirmation of uniform metadata, and formation of data composites.

The details of the data system will be described in the context of how it supports the Arctic researcher. This includes the ability to display and download data sets online, extract parameters from different data sets and create new composite data sets, and prepare and distribute project CDs. These capabilities are critical for supporting a number of Arctic regional data and model intercomparison efforts now underway or planned, as well as outreach activities to better inform the public of ARCSS research.

Field Project Support

JOSS is organized to help investigators with all facets of field project support, including guiding and assisting in developing sampling strategies, implementing support services such as an operations center or field catalog, and directly supporting field operations, including operations coordination and field data management services. The support may include organizing and leading site selection and a broad range of site arrangements including site preparation and modifications, contracting, workspace and laboratory infrastructure, communications, and information management. Project logistics including shipping and travel arrangements can be provided. JOSS has broad experience coordinating multi-agency and multinational facilities (aircraft, ships, and ground-based) at both domestic and remote foreign sites in field campaigns led by both U.S. and international scientists from numerous scientific disciplines.

Data Management Support to ARCSS Field Projects

The following description of support provided to NSF ARCSS field projects is based on 7 years of dedicated support to ARCSS-funded projects and 20 years of experience supporting multidisciplinary field projects around the world. The five ARCSS projects are:

- Surface Heat Budget of the Arctic Ocean (SHEBA), a multiphase international project to investigate the role of Arctic climate in global change;
- Arctic Transitions in the Land–Atmosphere System (ATLAS), a coordinated program that will examine the geographical patterns and controls over climate–land surface exchange and develop reasonable scenarios of future change in the Arctic;
- International Tundra Experiment (ITEX), a MAB NSN (Man and the Biosphere Northern Sciences Network) initiative established in 1990 to monitor the performance of plant species and communities on a circumpolar basis in undisturbed habitats with and without environmental manipulations;
- Western Arctic Shelf–Basin Interactions (SBI) project, a multiyear, interdisciplinary program to investigate the impact of global change on physical, biological, and geochemical processes over the Chukchi and Beaufort Sea shelf basin region in the western Arctic Ocean; and
- Arctic Regional Climate Modeling Intercomparison Project (ARCMIP), an international intercomparison of Arctic regional climate and mesoscale model simulations

JOSS data archives for ARCSS field projects. A total of 60.4 GB of data have been archived, processed, and made available to researchers.

Project Name	Years of Support	Volume of Data (GBytes)
SHEBA	1997–2003	49.7
ATLAS	1999–2003	2.7
ITEX	1999–2003	0.8
SBI	2001–2006	2.1
ARCMIP	2001–2004	5.1

A Workable Strategy

An integrated data management strategy is important to assure that complete data archives are provided to project scientists and the larger science community in a timely and efficient manner. Field projects benefit from the implementation of sound data management procedures and protocols before any data are collected. This includes the specification of a data policy, consideration of the data format, and development of documentation guidelines that maximize the ease of data exchange and archival. JOSS has implemented a data management system to facilitate submission, archival, and distribution of project-related data sets.

JOSS works with the science management offices, project offices, and individual investigators to support ongoing projects while fostering a consistent data management strategy that makes sense for the project's science objectives. JOSS assists the project scientists in determining data management requirements for the field phases and associated analysis periods to maximize efficient and timely data exchange. JOSS also collaborates with the Arctic Data Coordination Center (ADCC) at the National Snow and Ice Data Center (NSIDC) in the project planning phase to provide guidance to project investigators on effective data management strategies. This includes the provision of initial metadata for anticipated data sets. The ADCC provides a permanent archive location for data from all ARCSS projects.

The Field Catalog

If the project includes field phases, JOSS can provide a web-based, online field catalog or project web pages to support near-real-time documentation of activities and selected data displays. This also includes interactive access to common data sets of interest and sharing of preliminary data and analyses among project scientists who are in the field and elsewhere. The field catalog allows automatic and/or semi-automatic submission of field reports and data products (such as satellite images or preliminary research products and plots) for review and exchange while the field project is underway. Operational summaries, instrument status reports, daily mission plans, and other specialized reports are also ingested into the catalog.

The JOSS field catalogs in ARCSS-supported projects have proven to be valuable for reporting and monitoring operational activities and as a permanent archive of field activities. The catalogs from each field deployment, including ship cruises and multiyear field deployments, are kept in the JOSS archive and can be accessed at any future time.

Archival of Supporting Data Sets

Some field projects may require the collection of supporting data sets that add to the richness of the complete project data archive. JOSS typically completes a search of relevant available data and establishes data quality. High-resolution operational data (such as data available from national, regional, or local agencies) are often not routinely archived. Examples of these types of data include satellite imagery, numerical model products, high-time-resolution surface data from national or regional networks, and complementary data from nearby research projects. JOSS often makes special arrangements to archive these data for later access by project scientists.

Data Archive and Distribution System

JOSS has developed and implemented a Data Management System (termed CODIAC) that offers scientists a means to submit their data and accompanying metadata, identify and download other data sets of interest, display selected data sets online, and update data sets and documentation as necessary during the life of the project. For ARCSS, JOSS acts as an interim archive for field project data sets. This system provides a rapid turn-around of preliminary and updated data sets and password protection during the initial analysis period.

Since JOSS operates as an interim archive for ARCSS data sets, it is important to maintain close coordination with permanent archive centers. JOSS works with ADCC to assure timely transfer of data and documentation in a way that minimizes disruption to the access of project-related data sets.

Special Data Processing

It is possible to provide specialized processing for selected data sets, including quality control of data sets, parameter extraction from different data sets, and data set compositing (combining parameters from different data files or merging multiple data files). In addition, JOSS works with data providers and investigators to maintain consistent data formats and documentation for the supported project.

Finally, JOSS provides support to project scientists in integrating their data sets for education and outreach. This is done through online access to data and publications from the project and the compilation of CD-ROMs that focus on activities at a single site or region of the field deployment.

Specific Examples of Customized Support

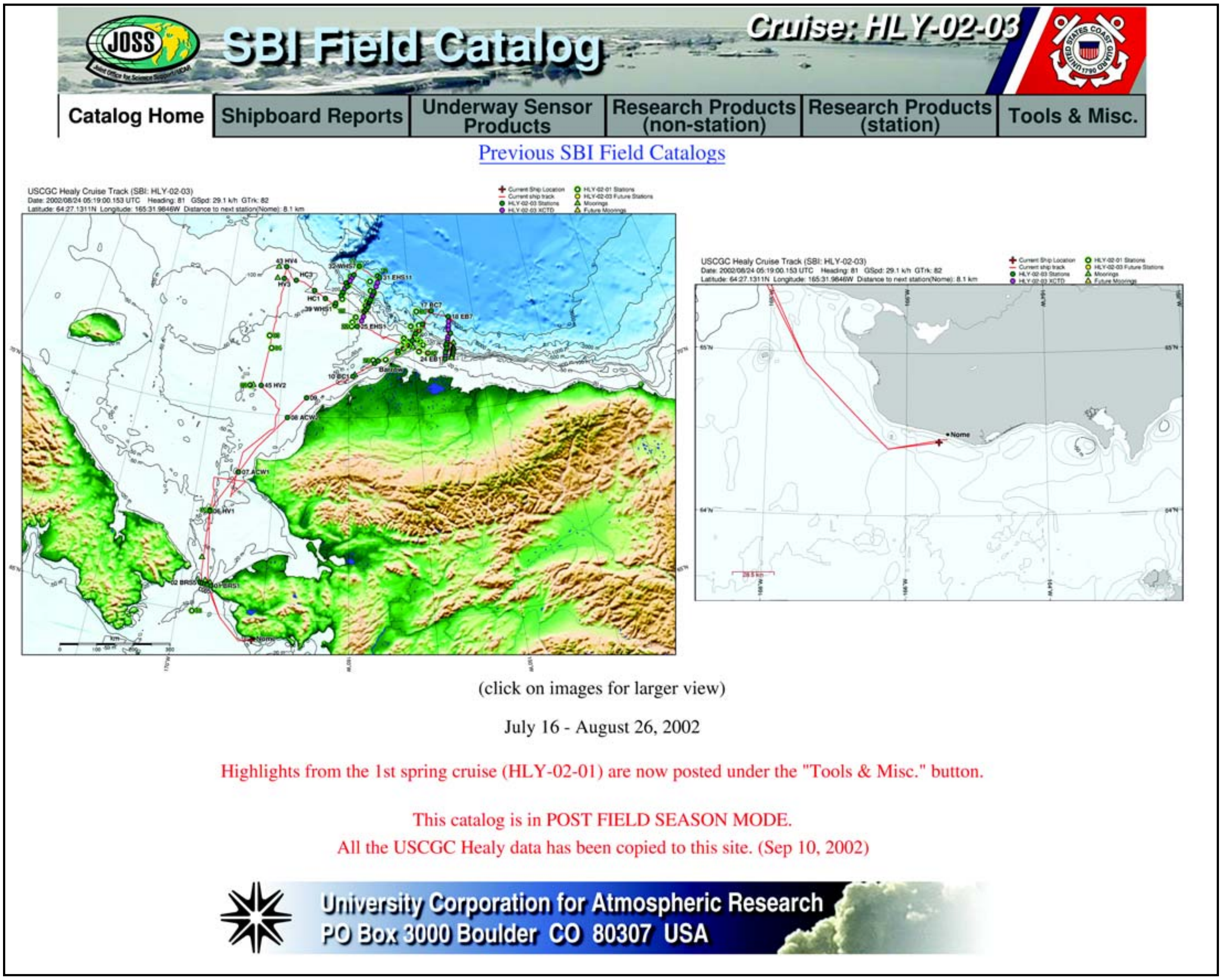
The general information presented above refers to services that JOSS provides to ARCSS projects as requested. The following examples show specific assistance that JOSS has given to projects.

The SBI Field Catalog was implemented by JOSS aboard the USCGC Healy *and is located at www.joss.ucar.edu/sbi. Navigation links access a variety of products that summarize the cruise operations. Products and reports are updated aboard ship as the cruise progresses. The larger regional image to the left shows the ship track with primary stations and mooring locations. The close-up image on the right provides details. Images are updated every 15–30 minutes.*

Support to SBI using the JOSS Field Data Catalog

During SBI, JOSS implemented an online field catalog during selected cruises to provide near-real-time documentation and browsing of operational data collected aboard ship. Previously deployed in the Arctic for the SHEBA project, the field catalog organized browse products and documentation for use in the field and provided a detailed field summary report for researchers after field operations ended. The catalog facilitated communication among researchers in the field and kept project participants abreast of ongoing operations. In addition, a portion of the shipboard catalog was routinely uplinked via satellite to the JOSS facilities in Boulder, Colorado. The mirror catalog in Boulder was used by project participants ashore, the USCG staff and families at home, the Arctic Eskimo Whaling Commission, and others interested in the ship's operations.

During SBI, two components of the field catalog were especially popular: a ship track plot updated every 15–30 minutes showing past and future station locations, moorings, and bathymetry (using data from the International Bathymetric Chart of the Arctic Ocean) relative to current ship position (see p. 27); and an event log detailing station activities, times, depths, and locations. In addition, during the spring cruise a form was implemented as part of the field catalog that allowed researchers to log detailed ice observations complete with digital photos and automatic reporting of current underway data from the ship, including position, water depth, and weather conditions.

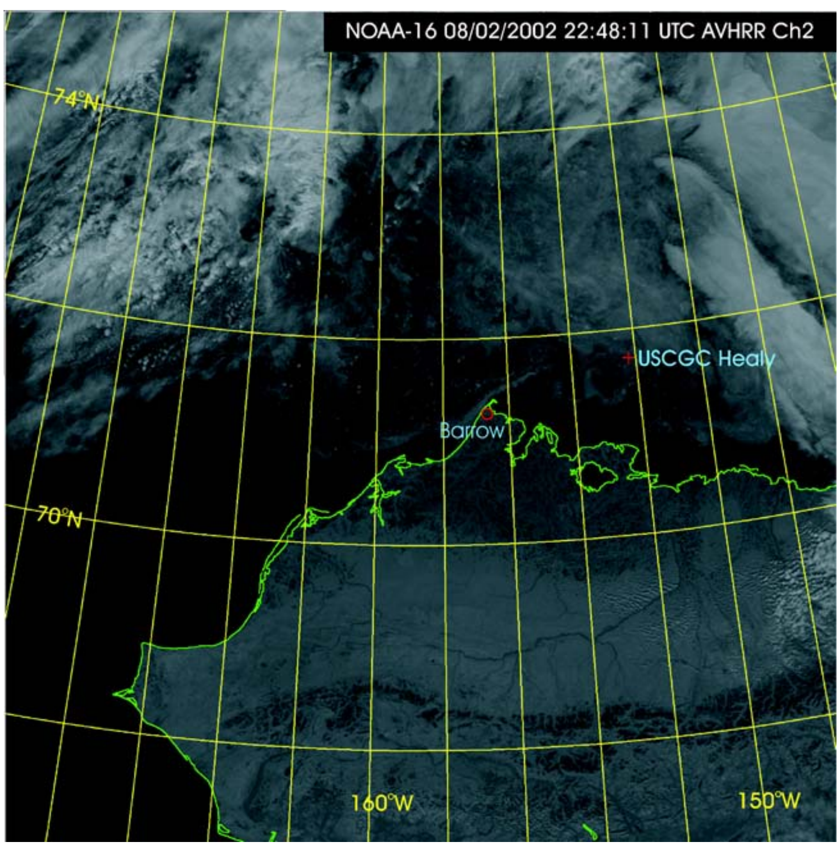


AVHRR imagery of northern Alaska and nearby Chukchi Sea from NOAA-16. This image was collected aboard the USCGC Healy during the summer SBI cruise of 2002. The position of the Healy at the time this image was taken is shown east northeast of Barrow. The image shows largely open water west of Alaska (black area), while sea ice of varying concentration exists in the Barrow vicinity and just offshore of the north coast. Significant cloud cover is seen in the northwestern and northeastern portions of the image and partially obscures the sea ice north of the Healy.

Catalog Products

One of the important features of the catalog architecture is that it allows customization of products and displays to meet the needs of the participants. Before the SBI deployment aboard ship, JOSS staff worked with the onboard scientists to put together a list of operational and research products that would aid in data analysis during and after the cruise. These products included:

- Satellite products [each overpass of NOAA and DMSP (Defense Meteorological Satellite Program) polar orbiters]:
  - 0.5-km-resolution visible images from DMSP satellites over an approximately 400- × 400-km area centered on the ship,
  - 1-km-resolution visible images from both types of satellites over an 800- × 800-km area centered on the ship, and
  - 3-km-resolution visible and infrared images over an approximately 1800- × 1800-km area centered on 70°N, 165°W;
- Ship track (updated every 15–30 minutes):
  - regional and zoom maps with track, stations, moorings, and bathymetry;
- Weather and other data (updated twice daily):
  - 24-hour time series plots of temperature, winds, pressure, humidity, and water depth;



- Research data (not station specific; spring cruise only):
  - ice observation reports (as frequently as every 2 hours when underway),
  - digital pictures of ice conditions, and
  - wildlife photos;
- Research data (station specific):
  - CTD data: WHP (WOCE Hydrographic Program) exchange format compressed (zip) files; comments on each cast; CSV (comma-separated value) format ASCII data; standard plots of temperature, salinity, oxygen, transmittance, photosynthetically active radiation (PAR), and fluorometer measurements; and vertical section plots of various parameters for station transects, and
  - bottle data: WHP exchange format files, bottle hydrographic reports, and synthesized vertical section plots of various variables for various station transects;
- Event logs:
  - detailed station event logs for each station with time and location, a map of the station location, both in-water and on-deck times, and Seabeam water depths for each event, based on daily logs generated by the U.S. Coast Guard;
- Reports:
  - chief scientist's daily operational summaries,
  - Teacher at Sea (TEA) daily journal reports (summer cruise only),
  - cruise summary reports for each principal investigator,
  - service team cruise summary reports, and
  - service team cruise science reports.

Post-Cruise Catalog Use

As mentioned above, a significant subset of all field catalog reports, ship location maps, satellite imagery, and periodic ice observations (spring cruise), as well as all station data, were mirrored to the JOSS facility in Boulder on a daily basis so that land-based co-workers and other interested parties could monitor ship operations. Ship location information was mirrored with a 12-hour time delay at the request of the Coast Guard because of security considerations. Research-quality data were protected for the principal investigators by implementing password control on the appropriate portions of the Boulder catalog. (This password protection will remain in place until the data enter the public domain.)

Near the end of each cruise, JOSS personnel onboard the *Healy* worked with service team members to produce a CD of the catalog station products, as well as all service data and other ancillary data sets produced during the cruise. These CDs were distributed at the end of each cruise to all interested parties, along with a CD copy of the ship's underway data files produced by the U.S. Coast Guard.

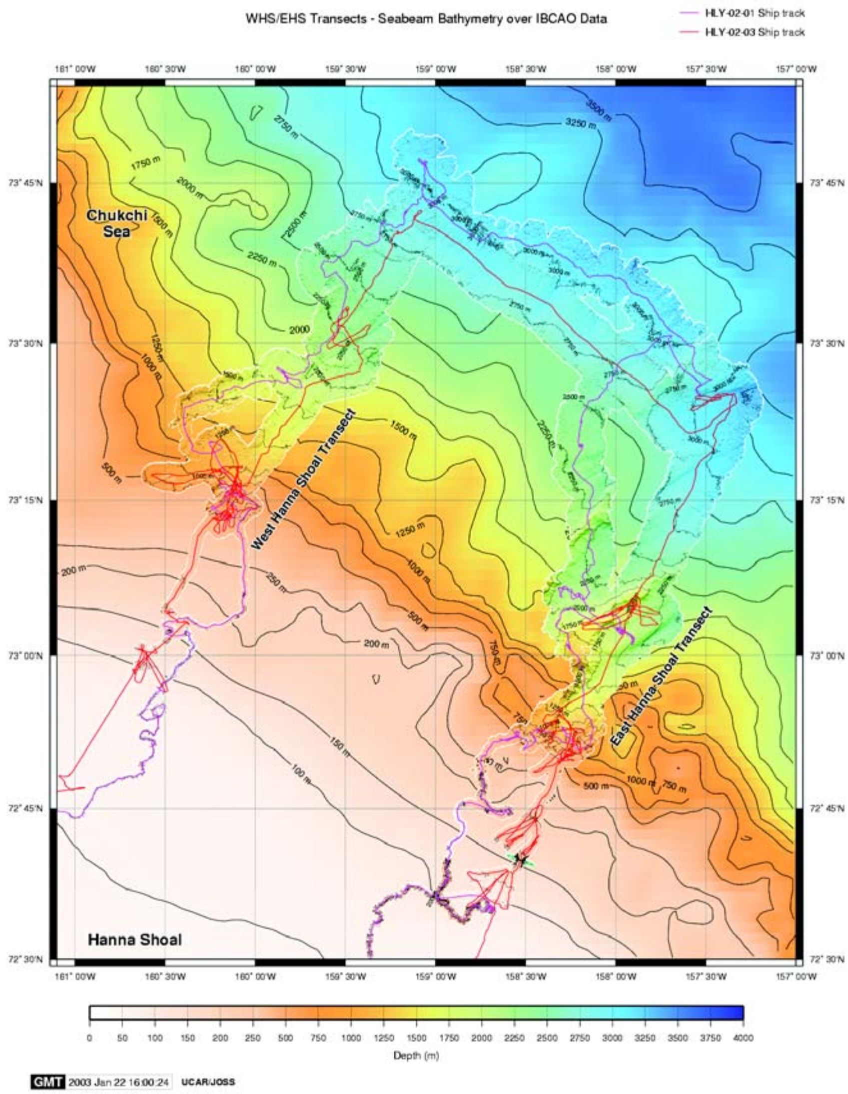
As part of JOSS's data management services during each cruise, several data sets were also collected and archived to tape for later availability through the SBI data archive at JOSS (http://www.joss.ucar.edu/sbi). Among these were satellite data pass files for each overpass of the ship by NOAA and DMSP polar orbiters. Information from the ship's log, including hourly weather conditions and operational times and locations, was also collected for the archive.

The complete field catalogs for both cruises are now online at JOSS (http://www.joss.ucar.edu/sbi/catalog). Consistent with the policy for NSF-sponsored research data residing at JOSS, research-quality data sets collected for SBI will be password protected for project participants for up to 2 years after collection to allow time for analysis and publication.

Data Management Web Sites for ARCSS Field Projects

JOSS works with project participants to establish data-management-oriented web sites that provide a single point of access to data and data-related products produced by the project. All JOSS-supported ARCSS field projects have web sites that can be accessed at http://www.joss.ucar.edu/arcss. Useful features common to all the sites include easy reference to the data management plan, data format and documentation guidelines,

The ATLAS Data Archive Page at JOSS. This page, located at www.joss.ucar.edu/atlas, is the gateway to ATLAS research data sets and supporting data at JOSS.



High-resolution Seabeam bathymetry data from the USCGC Healy *cruises (HLY-02-01 and HLY–02-03) overlaid on IBCAO bathymetry chart data in the same region. The two cruise tracks are shown by the red and magenta lines. Ship tracks that appear overlapping or confused are periods of free drift required for proper sampling. The thin black lines are isobaths. Note the fine-scale bottom details along the ship track derived from the Seabeam data.*

and simple data submission instructions. Access to the project data sets is available from the web page in several ways, including by year, by field site or cruise as appropriate, by discipline type, and by principal investigator. Other related links for access to distributed archive sites, project offices, or other relevant locations are provided as necessary.

Value-Added Data Processing

Bathymetric data from the Seabeam instrument were collected for each SBI cruise, along with data from the Knudsen and Bathy 2000 instruments. Maps were produced after decoding and replotting the Seabeam data, showing how much additional information about bottom characteristics can be available from these data. Currently available Arctic Ocean bottom topography from the International Bathymetric Chart of the Arctic Ocean Project provides the map background. This information will be crucial for the SBI scientists to interpret bottom samples taken during the SBI cruises.

JOSS can provide specialized support for the quality control of certain types of data collected for or by the field projects. JOSS worked with the ATLAS scientists and the NCAR Atmospheric Technology Division to perform checks on sounding data taken at the field site in Council, Alaska. JOSS has established specialized upper air sounding processing to help assure quality and uniformity in these data. JOSS received upper air sounding data from a variety of sources in multiple data formats and developed software to read and convert all of the soundings to the same columnar ASCII format. Three types of automated quality checks are applied to the sounding data. The checks confirm that the format conversion step was properly completed, verify that the data are within reason for the earth's atmosphere, and examine the vertical consistency of the sounding. None of the actual data within the sounding are changed, but quality-control flags are applied to specific data points and included with the sounding data. JOSS also visually examines a random portion of the sounding data to see if there are any consistent problems that the automated checks do not catch (such as humidity calculation problems). The data are then made available to the community via the Internet.

Consistent Project Data Format and Documentation Guidelines

One of the big challenges facing any field project is to collect the data in such a way that it permits simple and timely exchange with fellow participants and eventually with the larger science community. Considerable time is spent working with project scientists to reach agreement on data format and documentation guidelines. The following key components make up a successful data format structure:

- A consistent data file naming convention is defined so that files have unique identification, even for similar measurement types. Using an extension (such as .jpg or .txt) helps others users recognize the file format.
- Header record information includes contact information, temporal and spatial coverage, type of platform (such as ship or aircraft), coordinates (latitude and longitude), data ver-

sion number, and any other details of specific importance to that data set (such as measurement thresholds or a missing flag).

- Each row of data record includes a date and time stamp, the position, and the data. Alternatively each column following the date, time, and position stamp could be a parameter (with units) when multiple measurements are made at a single place or time.

The documentation that accompanies each project data set is as important as the data itself. This information permits collaborators and other analysts to become aware of the data and to understand any limitations or special characteristics of the data that may impact its use elsewhere. The data set documentation should accompany all data set submissions. While it will not be appropriate for each data set to have information in each documentation category, JOSS's guidelines should be adhered to as closely as possible to make the documentation consistent across all data sets. It is also recommended that a documentation file submission accompany each preliminary and final data set.

Project Data Documentation Guidelines

TITLE: This should match the data set name

AUTHOR(S):
-Name(s) of PI and all co-PIs
-Complete mailing address, telephone/fax numbers, web pages, and E-mail address of PI
-Similar contact information for data questions (if different than above)
-Grant number and title

DATA SET OVERVIEW:
-Introduction or abstract
-Time period covered by the data
-Physical location of the measurement or platform (latitude/longitude/elevation)
-Data source, if applicable
-Any World Wide Web address references (additional documentation such as the project's WWW site)

INSTRUMENT DESCRIPTION:
-Brief text (1–2 paragraphs) describing the instrument with references
-Figures (or links), if applicable
-Table of specifications (such as accuracy, precision, or frequency)

DATA COLLECTION and PROCESSING:
-Description of data collection
-Description of derived parameters and processing techniques used
-Description of quality control procedures
-Data intercomparisons, if applicable

DATA FORMAT:
-Data file structure, format, and file naming conventions (for example, column-delimited ASCII, NetCDF, GIF, JPEG)
-Data format and layout (description of header/data records, sample records)
-List of parameters with units, sampling intervals, frequency, range
-Description of flags, codes used in the data, and definitions (such as good, questionable, missing, estimated)
-Data version number and date

DATA REMARKS:
-PI's assessment of the data (disclaimers, instrument problems, quality issues, missing data periods)
-Software compatibility (list of existing software to view/manipulate the data)

REFERENCES:
-List of documents cited in this data set description

Preparation of Specialized Analysis and Outreach Products

As part of its support to ATLAS, JOSS worked with project scientists to compile the first of several data CDs that will be used to share useful data and information from the project with Arctic researchers, as well as educators, students, and other interested users. The initial CD is a compilation from the Ivotuk site on the North Slope of Alaska. The introductory web site contains data, photos, and descriptions gathered by more than 30 scientists and technicians encompassing a 2.5-year period from early 1998 through June 2000. The main purpose of the CD is to provide a single archive source for the multidisciplinary data collected at this site, in addition to presenting an overview of the project for those interested but not conversant with the individual disciplines.

The CD was designed to be operate using Windows or Macintosh and most web browsers. The principal features of the CD are:

- A self-contained archive on a single CD;
- Interactive site maps;
- Overview information on site and group activities;
- Cross-referencing of data by site, group, discipline, and year using menus, tables, and maps;
- Detailed data documentation; and
- A slide show and other sequences of interest.

Considerations for the Future

The Arctic research scientist of the future will be able to deploy or redirect assets that are mobile, long range, and easily relocated. They will want more data in near real time to assist with the monitoring and assessment needed to use deployed facilities and instrumentation more effectively and safely. The need and availability of data and products in real time during field campaigns will increase as researchers conduct more complex experiments and deploy facilities and instrumentation remotely. Remote campaigns in the future can be linked directly to the classroom involving students at all levels in the scientific enterprise.

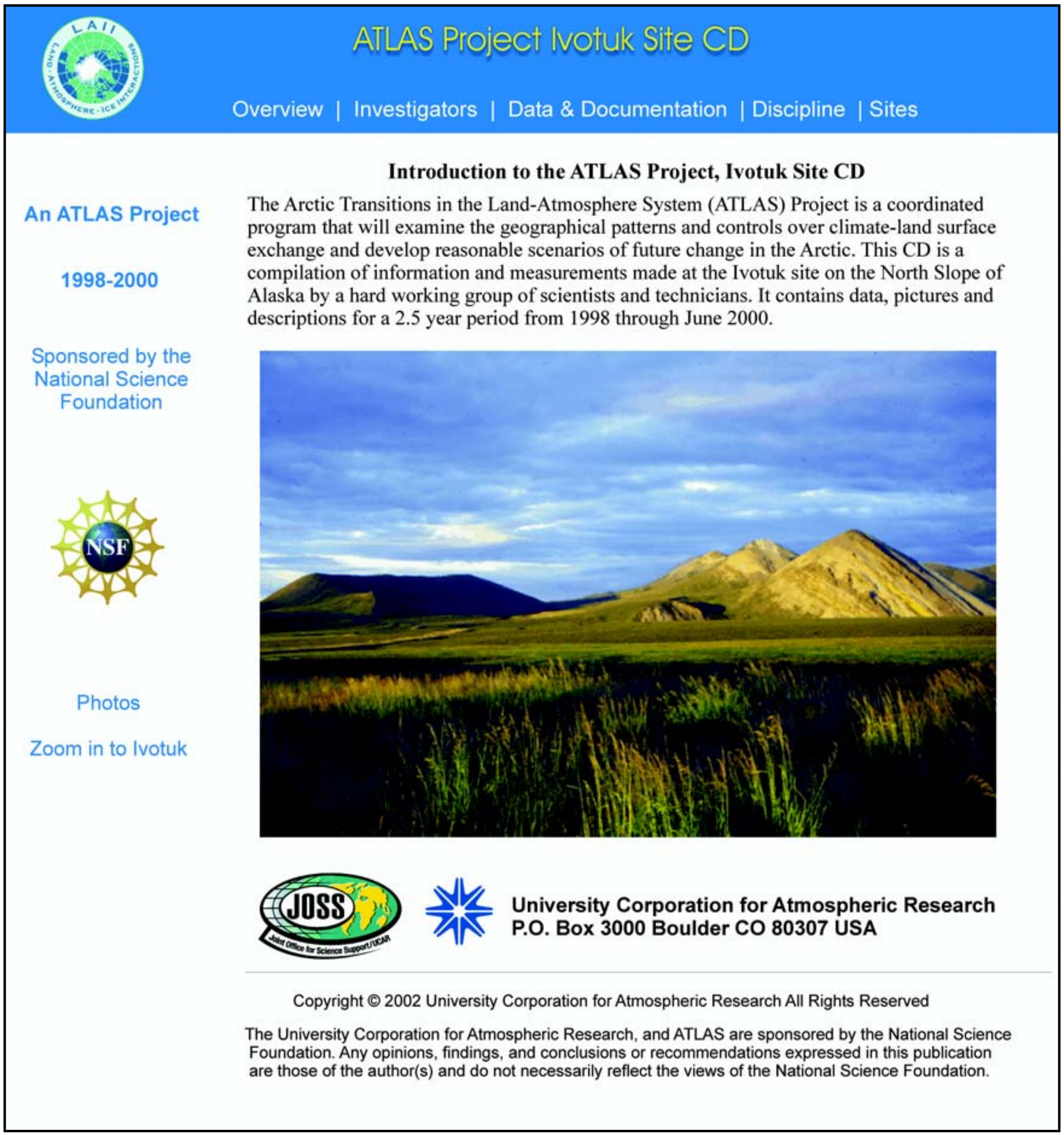
Data interoperability, or incorporation of data into a single analysis or visualization environment from distributed archives, will be standard for earth science researchers.

The researcher of the future will have seamless web access to project data, using high-bandwidth network connections and powerful data visualization, retrieval, and analysis tools. JOSS seeks to develop these tools and capabilities in its data management system.

There will be an increasing interest in multidisciplinary synthesis of data sets as the research community scales up beyond basic research to address regional and global climate questions. The science community must be able to draw in data sets efficiently and reliably from distributed data archives to create the analysis data sets needed to address these important questions.

JOSS will continue to work hard to support the efforts of ARCSS and provide a phased approach by providing continuing assistance to new projects such as SEARCH and the Freshwater Initiative. They will take every opportunity to implement new technologies, matching the requirements and capabilities outlined above in an effort to aid the scientists in achieving their science objectives.

The ATLAS Project Ivotuk Site CD page at JOSS. This page, located at www.joss.ucar.edu/atlas/ivotuk_CD/html/IvotukFrameset.htm, is the online interface to the complete CD. Interactive maps, a zoom movie, annotated slide shows, and many data plots are some of the features of the CD.



The Arctic System Science Data Coordination Center

Playing a Vital Role in ARCSS Knowledge Synthesis

This article was prepared by Nancy Auerbach, ARCSS Data Coordination Center (ADCC), National Snow and Ice Data Center, University of Colorado, Boulder; Yarrow Axford, Institute of Arctic and Alpine Research, University of Colorado, Boulder; Rudy Dichtl, ADCC; Michael Hartman, National Climatic Data Center; Chris McNeave, ADCC; Betsy Sheffield, ADCC; and Keri Webster, ADCC.

The Arctic System Science Data Coordination Center (ADCC) is the central, long-term archive for data collected by the NSF's ARCSS program. The ADCC is located at the National Snow and Ice Data Center (NSIDC) at the University of Colorado, Boulder, a national information and referral center supporting polar and cryospheric research. The primary goals of the ADCC are to collect and preserve ARCSS data and to make those data easily accessible to ARCSS investigators, the scientific community, policy makers, and the general public.

As indicated by the program name, ARCSS promotes the concept of system science, or the integration of knowledge from various Arctic disciplines. This synthesis depends on the accessibility and exchange of data among members of the scientific community. Published research findings focus on final results and target a specific discipline, but researchers can use raw data for reasons that differ from the original reason for collecting the data. Because of this potential, a long-term archive of ARCSS data, with its accompanying metadata, is valuable to the ARCSS program in particular and the scientific research community as a whole.

Having a central point of focus for ARCSS and its data is essential to a program aimed at understanding global change. This is especially true because the ARCSS program focuses on the science of environmental systems and is defined geographically, rather than by discipline. ARCSS supports many projects collecting a diverse set of data.

The ADCC ensures public access to ARCSS research data. It maintains high standards for data management to meet the needs of the current users of the ARCSS data collection, as well as to ensure the long-term viability of the data.

History

NSIDC received its first grant for ARCSS data management in 1990 for support of GISP2. NSIDC also received individual data management grants in 1991 and 1992 for the OAII and LAII programs, respectively. Following the success of these grants, and with the increasing interest in global climate change research, the need for a continuous record of collected environmental data became clear. In 1994, NSIDC received the first grant for creating the ADCC, a distinct entity within NSIDC charged with managing and archiving all ARCSS data. NSF granted a continuation award of the same title in 1997 and a supplemental award in March 2001.

The ADCC remains housed within NSIDC, which has a long and successful history of data management. NSIDC's roles include:

- Serving as one of eight Distributed Active Archive Centers funded by NASA;
- Acting as a national information and referral center supporting NOAA's National Environmental Satellite, Data, and Information Service;
- Providing data and information services to the user community, publishing reports and a quarterly newsletter, and maintaining a large library collection of monographs, technical reports, and journals;
- Contributing to international programs concerning the cryosphere and its role in climate; and
- Supporting the NSF through the ADCC and the Antarctic Glaciological Data Center.

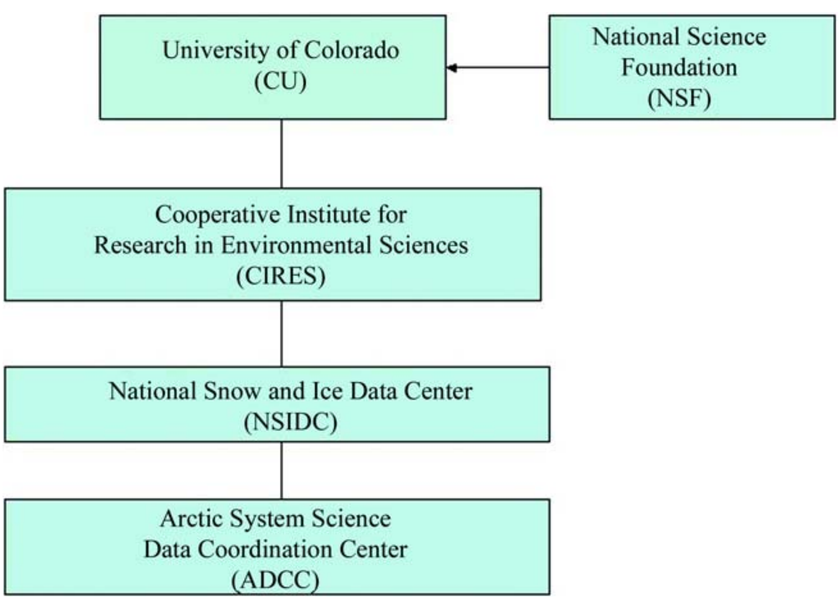
ADCC's relationship with NSIDC is highly beneficial to the ARCSS program. As an umbrella organization, NSIDC has a larger staff that provides operational support, user services support, tape archiving, computer system administration, administrative assistance, writer services, programming support, and other services, on a cost-reimbursable basis. The ADCC also benefits from shared computing and network infrastructure, as well as common data management policies and procedures. Cost sharing and collaboration with NSIDC extends the ADCC's capabilities far beyond what ARCSS funding could support alone.

Until the ADCC was founded, data were usually made publicly accessible, at the discretion of the investigator, through structured data centers. Published final results were available, but the raw data were not distributed as frequently. Therefore, the ADCC focused initially on collecting raw data from the then-small community of ARCSS scientists. These data were usually structured or documented in a manner easy for the principal investigator (PI) to understand and use. However, the data were often difficult for other users to understand without the involvement of the collecting investigator to help define variables, column headings, or data location information. As a result the ADCC began to request that ARCSS PIs submit substantive metadata (information about data) to the ADCC along with their data. This shift in focus from collecting only raw data to collecting the supporting metadata as well has helped to ensure long-term viability of ARCSS data.

Data Management and Processing

Researchers must consider data management as early as possible in the development of new research projects. Therefore, the ADCC is involved in all ARCSS science committees. The ADCC participates in planning new ARCSS initiatives to offer data management insights and anticipate future archive needs. When developing data management plans for evolving ARCSS projects, the ADCC considers the broad range of program needs to determine how incoming data will be processed and distributed.

The relationship of the ADCC to the NSIDC and NSF.



The ARCSS Data Protocol is well established and has been widely adopted by the various ARCSS Science Management Offices (SMOs). The key assertion of the data protocol is that all ARCSS-funded data are considered "community property." ARCSS PIs will retain exclusive use of their data for one year after collection. After the first year, their data are released to other ARCSS investigators, and after two years the data must be released to the public domain via the ADCC. The data protocol is available at http://arcss.colorado.edu/arcss/protocol/protocol.html.

Working with PIs

Initially the ADCC conducted project and all-hands meetings as opportunities to solicit data. Although capable of reaching large audiences, this method of contact was inefficient and didn't allow for more personal interactions. As a result, in July 2000 the ADCC began sending "first contact" email messages to PIs of newly awarded grants, offering congratulations and laying the groundwork for later data submission. These messages acquaint PIs with the ADCC and make preliminary recommendations for appropriate data formats to ensure maximum flexibility and data sharing in the future. They also direct PIs' attention to the ADCC web site and the online metadata submission form.

ADCC subsequently sends a second contact letter to all PIs reminding them of the need to submit their data to the ADCC. This occurs about a year after the first contact letter, presumably after the first field season has passed and after the PI has had the opportunity to plan for data submission. In the second letter the ADCC requests information about the expected types of data and their projected date of availability. Once that date arrives, the ADCC contacts the PI to plan for data transfer and to request that the PI submit metadata via the online metadata submission form.

Working with JOSS

The ADCC collaborates closely with the Joint Office of Science Support (JOSS), a University Corporation for Atmospheric Research (UCAR) organization, and the ARCSS SMOs to develop data management procedures that define the roles of both JOSS and the ADCC and to communicate these procedures to each ARCSS PI. A current example of this collaboration is the coordinated effort to provide the Arctic-CHAMP project SMO with a complete data management plan to meet all of Arctic-CHAMP's requirements. JOSS and the ADCC have unique and complementary services that serve the specific needs of the PIs among the 18 awarded CHAMP projects and the SMO.

PIs who are involved with certain large ARCSS projects, such as SHEBA, ATLAS, and ITEX, initially submit their data to JOSS (http://www.joss.ucar.edu/arcss). JOSS maintains a restricted-access, interim archive for near-real-time data presentation. JOSS's primary role is early data collection to provide field support by redistributing project data back to other project scientists for their immediate review and evaluation. During this period of initial collection, the ADCC and JOSS meet to plan and organize the pending transfer of data and metadata. Often data are in a preliminary state, and the ADCC works closely with JOSS to coordinate the final effort to bring the data up to the standards required for long-term archival. Once a field project has concluded, JOSS transfers its holdings to the ADCC, and the ADCC works with individual PIs to finish bringing data and documentation up to the final standards.

Overall the function of JOSS is to make data physically accessible as quickly as possible and to provide a variety of supporting data from other disciplines (for example, weather forecasts for in-field operational areas). Once data are transferred to the ADCC, the goal is to make data sets intellectually accessible as well as physically accessible. The ADCC ensures that data sets go through a thorough quality assurance process and that the associated metadata and documentation are complete and accurate.

Receiving Data and Metadata

Metadata must accompany data in a long-term archive to ensure the longevity of the data as well as their usefulness to a broad audience. Numerous examples demonstrate that data can become useless if relevant metadata are missing. Metadata may include information such as variables measured, spatial and temporal coverage, data format, and weather conditions during data collection. The ADCC's emphasis on metadata and documentation is one important factor that sets it apart from other archives that lack a long-term perspective.

The ADCC has created an online metadata submission form that streamlines the metadata submission process, making metadata compilation more efficient for PIs and the ADCC. Furthermore, the form *requires* that PIs submit at least a minimum of metadata, ensuring that the ADCC obtains appropriate metadata early in the data submission process. PIs access the metadata submission form through the ADCC web site (http://arcss.colorado.edu/forms/arcss_submit.html). PIs may submit raw data in any form but must use the metadata submission form to send their metadata. The data coordinator reviews both the metadata and the data to ensure that they are complete and that the information provided properly describes the data. The coordinator immediately asks the PI about any incomplete or inconsistent items, so the PI can make corrections.

While the quality control of actual data values is the responsibility of the PI collecting the data, the ADCC performs quality assurance (QA) of the metadata and overall data set. This QA ensures the long-term viability of the data set for users other than PIs who have intimate knowledge of the data or project. The ADCC conducts a thorough check of the data's integrity, accuracy, column headings, and units, comparing them with the documentation that the PI submits with the data.

Creating Documentation

Following the QA process, the ADCC project writer prepares the data set documentation. To assist PIs in meeting metadata requirements, the ADCC produces two types of data set documentation, based on information that PIs submit with their data: a data interchange format (DIF) file and a summary document. Both standardize a data set's metadata, increase ease of use, and allow future access to that data set. The DIF is the metadata file format used by NASA's Global Change Master Directory (GCMD) and is compatible with International Standards Organization (ISO) and Federal Geographic Data Committee (FGDC) metadata standards. The ADCC submits every DIF it writes to the GCMD, which is part of the U.S. Global Change Research Program. Thus, every ARCSS data set appears in the GCMD's searchable database and is visible to the broader global change research community. In writing and submitting DIFs to the GCMD, the ADCC provides an additional service to PIs, who would otherwise be required by NSF to do so themselves. The DIFs are the internal NSIDC metadata standard and are used to automatically generate the ADCC's online data catalog entries for each project.

The summary documents contain all available metadata for each data set and are often much more comprehensive than the DIFs, providing detailed information about data collection methodology, file structure, tools for accessing data, and other data characteristics. They also describe how to appropriately cite the data set, with the scientists as authors and the ADCC as publisher. Documentation files are packaged with the data and are accessible via the online data catalog entries.

Once the data and documentation are ready for publication, the ADCC team and NSIDC user services personnel review the data set. They identify problems or questions that a user may encounter and take the appropriate corrective steps, in collaboration with the PI, prior to the release of the data on the file transfer protocol (ftp) site or on CD-ROM.

Providing Data Security and Interoperability

The ADCC has established a system for maintaining backups that are safely stored, technologically current, and accessible. This system includes archive files, regularly scheduled backups, off-site backup tape storage, and strategic planning for upgrades. The ADCC creates an archive of each ARCSS data set that includes data and documentation preserved as originally submitted, as well as the quality-assured versions presented on the ADCC web site. A full backup of the ADCC server is performed monthly, and backup tapes are rotated to an off-site location on the University of Colorado's main campus. Additionally, ensuring that a data set remains uncorrupted while it is transferred to ADCC, used, and maintained is important. The ADCC is investigating the use of algorithms to determine the continued integrity of all data sets within its holdings.

Assuring long-term data security is a top priority, so the ADCC participates in NSIDC's long-term archive committee planning. The committee is responsible for defining NSIDC's data management policies, assuring interoperability between systems, and developing and implementing strategic plans for long-term management of NSIDC-hosted archives. Additionally, security plans are in place for all NSIDC systems. System components are reviewed periodically for risk assessment. Systems are monitored daily for intrusion detection, and relevant Computer Emergency Response Team (CERT) bulletins are addressed as soon as possible.

Special Data Handling

In addition to data products archived within the ADCC, various programs and PIs have data that require special handling. Some projects archive their data with alternative permanent archives, such as those maintained for the Long-Term Ecological Research (LTER) program. PIs working on such projects are required to provide the ADCC with enough information so that it can maintain referring links to the alternative archive locations as well as list the data in the ADCC online data catalogs and within the GCMD.

Similarly a PI may have a unique distribution site to which data are frequently added and updated. The ADCC provides a link to this site and lists it in the online data catalogs. However, because of the dynamic nature of such a collection, rather than duplicate the collection and attempt to maintain version control, the ADCC periodically downloads the PI's content for backup and storage in the event that the originating site ceases operation or experiences unrecoverable loss.

Model output is another special case that the ADCC takes into account. ARCSS research includes the development of environmental models that provide a unique set of challenges for data management. The ARCSS Model Output Protocol addresses these concerns. The policy stipulates that PIs who are developing models should provide the ADCC with descriptions of their models so that other investigators are aware of what work is being done, and PIs should work with the ADCC to determine which model output data are suitable for archiving. For output to be archived at the ADCC, the model must be published in a peer-reviewed publication, fully documented, and in a completed state. If these criteria are not met, or if the output is too voluminous to be feasibly distributed, the ADCC directs users to the PI's web site or an appropriate contact person.

The HARC project is one that has unique data management needs. Handling HARC data involves additional planning by the PIs and the HARC SMO because of the potential sensitivity of social-science-related data and information. PIs, working with the SMO, must decide which data are to be transferred to the ADCC for open distribution. Additionally, for any HARC data set that is archived at the ADCC, PIs must supply documentation of the informed-consent process and proof that all regulations concerning the protection of human subjects have been met.

The PARCS SMO has its own data management system and archive. That office is responsible for archiving all PARCS data and for interfacing with other ARCSS programs and global change data efforts. The ADCC does not list individual PARCS data sets in its catalog but provides a link directly to the PARCS data archive (http://www.ngdc.noaa.gov/paleo/parcs/data.html).

Non-ARCSS Data

In several cases the ADCC has accepted data that were not collected by ARCSS-funded investigators but have been identified by ARCSS PIs as important adjuncts to their data. For example, the ADCC has accepted some Scientific Ice Expeditions (SCICEX) data for its long-term archive. Even though SCICEX is funded partly by the Arctic Natural Sciences program, there was enough interest in these data among ARCSS scientists to justify collecting them for long-term support. Similarly the SHEBA Reconnaissance Imagery data set (http://arcss.colorado.edu/data/arcss200.html) is a large collection of images that

Sample ADCC data set catalog page.

nsidc.org data projects research the cryosphere news site map

NSIDC catalog search tools help features

Soil Descriptions and Soil Chemistry for LAII/ATLAS Winter Carbon Flux Sites, Alaska, 1992 and 1998-2000

Documentation Access Data

Soil profiles at 27 sites in northern Alaska were described and classified in order to provide baseline soils data for ARCSS/LAII/ATLAS (Arctic Transitions in the Land-Atmosphere System) Winter Carbon Flux studies. The investigators collected samples and field data in the summers of 1992, 1998, 1999, and 2000. Profile descriptions include horizon depth, color, texture, and other morphological properties. Accompanying sample site descriptions provide information about landforms, vegetation cover, and soil parent material. Soils are classified according to USDA soil taxonomy guidelines. Laboratory analyses include measurements of soil water content, bulk density, texture, organic matter content, carbon storage, pH, and chemical components including carbon, nitrogen, calcium, phosphorus, potassium, aluminum, manganese, and iron.

Profile descriptions, laboratory data, and soil pit photographs and profile sketches are available via ftp in MS Excel, MS Word, and .JPG formats.

Data Citation

C.L. Ping, V. Romanovsky, G.J. Michaelson, and W. Lynn. 2002. Soil descriptions and soil chemistry for LAII/ATLAS Winter Carbon Flux Sites, Alaska, 1992 and 1998-2000. Boulder, CO: National Snow and Ice Data Center. Digital media.

Data Location Maps:

Location of sample sites:

See Also:

- User Services

ADCC ARCSS catalog

Data Contributors

- PING, CHIEN-LU
- ROMANOVSKY, VLADIMIR
- MICHAELSON, GARY J.
- LYNN, WARREN

Parameters

- ALPINE/TUNDRA
- CARBON
- NITROGEN
- ORGANIC MATTER
- PHOSPHORUS
- POTASSIUM
- SOIL BULK DENSITY
- SOIL CHEMISTRY
- SOIL CLASSIFICATION
- SOIL COLOR
- SOIL HORIZONS/PROFILE
- SOIL MOISTURE/WATER CONTENT
- SOIL PH
- SOIL STRUCTURE
- SOIL TEXTURE

Instruments

- CARBON ANALYZERS
- CHN ANALYZERS > Carbon, Hydrogen, Nitrogen Analyzers
- PH METERS
- SOIL SAMPLER

The National Snow and Ice Data Center (NSIDC)
Supporting cryospheric research since 1976
CIRES, 449 UCB University of Colorado Boulder, CO 80309-0449

were adopted because of their relevance to the SHEBA project. Another example, the Physical and Chemical Properties from Selected Expeditions in the Arctic Ocean data collection (http://arcss.colorado.edu/data/arctic_ocean_expeditions/), is a growing collection of oceanographic data that will eventually include data from more than 20 Arctic Ocean cruises.

An additional non-ARCSS-funded initiative is the recent collaboration between the ADCC and the University of Colorado. The ADCC will acquire, prepare, and release high- and low-resolution imagery and a digital terrain model of Barrow, Alaska. High-resolution imagery will be available to NSF-funded researchers, while low-resolution versions of the data sets will be released to the general public. Data set releases are scheduled for later this year.

Data Presentation and Distribution

The ADCC Web Site

The ADCC web site serves as the primary tool for data archiving and distribution to scientists and the public. The web site provides an online data catalog, information about the ARCSS program and its projects, contact information for all ARCSS PIs, and an invitation to PIs and the public to contact the ADCC.

Entries in the online data catalog uniformly describe each data set, including data contributors, parameters (such as valid variables as defined by the GCMD), instruments, data citations, and related links. Most catalog entries also display sample location maps. Search tools help users locate data sets by project name, NSF grant number, name of PIs and co-PIs, and measured parameters. Additionally an NSIDC-wide data catalog search engine (http://nsidc.org/data/search. html) allows for a free-text search of any words appearing in the DIF metadata files.

Geographic Information Systems

The ADCC uses geographic information system (GIS) software as a tool to spatially represent data location or data visualization displays through maps accessed from the ADCC online data catalog pages. Maps vary, depending on the data set. GIS software is a valuable tool for the ADCC to use for creating data location maps and visualizations of data and for providing improved data access and searching. The ADCC uses the functionality of GIS to enhance the accessibility of data and does not analyze, manipulate, or alter submitted data. The ADCC can customize data sets by producing either static image maps or interactive maps served using an Internet map server (ArcIMS by Environmental Systems Research Institute).

Data Collection Location Maps

Data location maps assist users in quickly determining whether data sets are located in a region of interest. PIs provide spatial coordinates of data collection points or areas when submitting their data to the ADCC. From these coordinates, the ADCC creates standardized location maps and includes them in the online data set catalog entries. More complex data sets require other means of displaying data collection points, for example, in "rollover" maps.

Data set locations may also be displayed via interactive maps served over the Internet. The maps may be queried and subsets of the data accessed interactively through a web browser. At present, two data sets have been enabled on a trial basis using an Internet map server (ArcIMS by Environmental Systems Research Institute): Russian Historical Soil Temperature Data and SCICEX Hydrographic Data.

Data Visualization Displays

Spatial (mapped) data displays assist users in visualizing data sets that are in vector or raster formats. The ADCC produces two types of data visualization displays: thumbnail images of data sets and interactive maps. Both help users assess, before downloading, whether a data set meets their needs.

Thumbnail sketches provide a visual overview of data, whereas interactive maps provide more detailed information. For example, the ADCC has produced various ArcIMS-enabled maps in collaboration with University of Colorado researchers at the Arctic North Slope Climate Impact Assessment (ANSCIA) component of HARC. The interactive maps display spatial data to interested researchers and can inform the public (in this case, the residents of Barrow, Alaska) about research being conducted in their vicinity. The ADCC web site displays data from the ANSCIA program at two scales: the North Slope region and the Barrow vicinity.

To view sample GIS maps from the ADCC, visit the following links:

Rollover maps
http://arcss.colorado.edu/data/docs/arcss/arcss07/iloc079.html

Russian historical soil temperature data
http://adcc.colorado.edu/arcims/website/arcss078/

SCICEX hydrographic data
http://adcc.colorado.edu/arcims/website/arcss064/

Sample thumbnail sketch
http://arcss.colorado.edu/data/docs/arcss/arcss017/access017_tlk500.html

ANSCIA program: North Slope region
http://adcc.colorado.edu/arcims/website/harc_northslope

ANSCIA program: Barrow vicinity
http://adcc.colorado.edu/arcims/website/harc_barrow

CD-ROM Publication

The ADCC uses CD-ROM media to distribute large ARCSS data sets and other information that are too large to transfer online. CD-ROM publication usually coincides with the creation of a special product, acquisition of a large volume of data from one project, or a grouping of data products for ARCSS research.

CD-ROMs have several advantages for some users:

- They enable users to take data with them into the field and to use data in remote locations without Internet connections.
- They can provide educational and outreach materials to classrooms.
- Users with limited computer network capacity for data transfer (in developing countries, for example) can benefit from data provided on CD-ROMs.

To date, the ADCC has distributed four CD-ROMs:

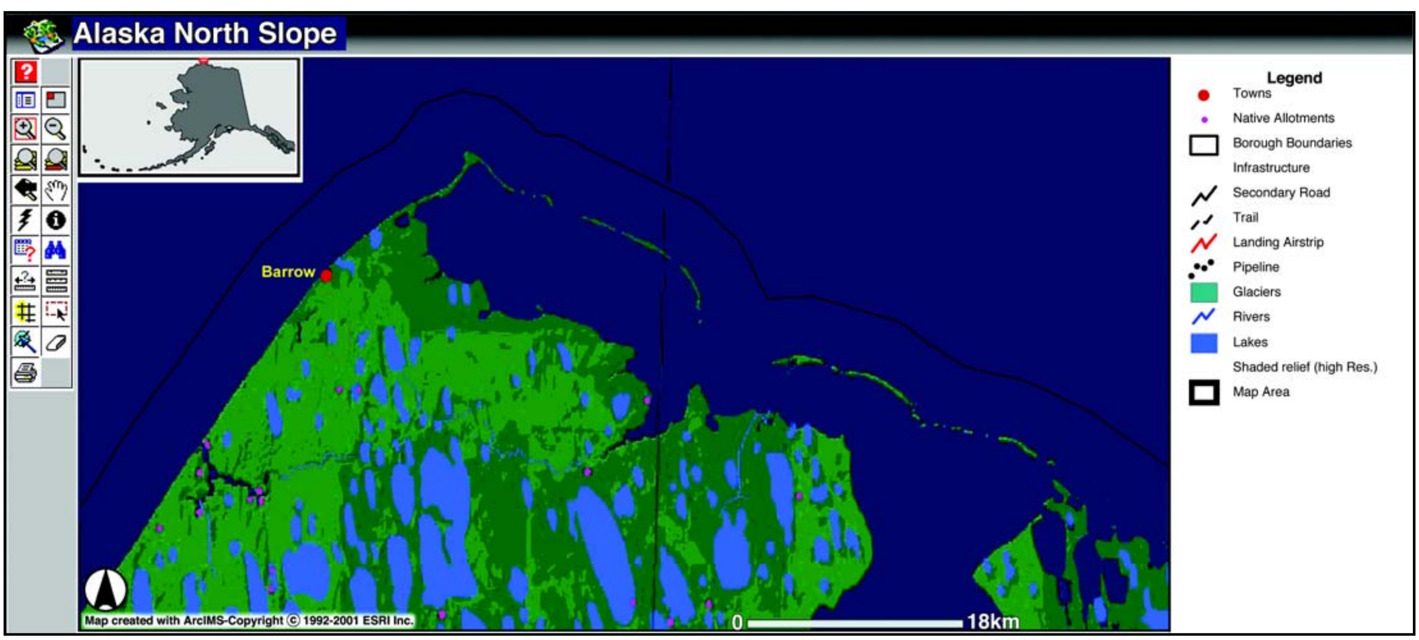
- *Greenland Summit Ice Cores (GISP/GRIP)*;
- *Into the Arctic*;
- *Circumpolar Active-Layer Permafrost System (CAPS)*; and
- *R-Arctic Net: A Regional Hydrographic Data Network for the Pan-Arctic Region*.

Outreach

In addition to the web site, the ADCC is involved in other efforts to communicate with PIs, the scientific community, and the general public. The ADCC makes frequent presentations at ARCSS-related meetings and general workshops to inform users, potential users, and contributing PIs about the ADCC and its data archiving and presentation goals. These presentations show how ADCC data sets are applied, the importance of complete and thorough metadata submissions, the need for long-term archiving of data sets, and the accessibility and usability of the data sets already on the ADCC web site.

To help promote Arctic education, the ADCC created the *Into the Arctic* CD-ROM. *Into the Arctic* allows teachers and students to access earth science data collected by research scientists studying climate change. This educational product provides data and information acquired from Greenland ice cores and includes lessons and activities appropriate for high school and college earth science, geography, history, social studies, and chemistry courses. This product has been

Sample interactive online map.



accepted by NASA and is listed in its 2002 catalog of approved Earth Science Education Products (http://earth.nasa.gov/education/index.html).

Future Directions

The NSF recently released a 10-year outlook for its Environmental Research and Education portfolio. The report, *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century,* was written by the NSF Advisory Committee for Environmental Research and Education. NSF Director Rita Colwell said, "NSF should move in the direction of synthesis of environmental knowledge."

To help promote this synthesis, the ADCC will:

- Continue its support of all newly initiated ARCSS projects. By identifying new initiatives early in the data management process, the ADCC will help new projects and SMOs receive the required data management support as early as possible.
- Increase focus on long-term archiving of data sets, with particular emphasis on data recovery policies and the use of backup media. The ARCSS program management has identified long-term data management as a priority.
- Contribute to the development of a data management plan that will integrate with the ARCSS Program Plan. The ARCSS Committee, made up of active PIs concerned about future research activities, will redefine key components of ARCSS and help promote research among all ARCSS programs. A special subcommittee on data management will create a data management plan, with input from the ADCC, that will integrate with the overall ARCSS Program Plan.

The concept of system science, or the integration of the Arctic sciences, depends on the accessibility and exchange of data among varying scientific disciplines. Long-term preservation of knowledge and the metadata to readily access that knowledge are key to ensuring that data offered have value beyond the goal of the initial collection. The ADCC, through its long-term data archiving and efforts to make ARCSS data easily accessible, will continue to promote the goals of system science.

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