


An aerial photograph of a vast, snow-covered landscape, likely a tundra or a coastal plain. The snow is uneven, forming soft, rolling dunes and ridges. Long, dark shadows are cast across the snow, indicating a low sun position, possibly during the winter months. The overall color palette is a mix of bright white and soft, pale blues and greys, creating a serene and somewhat desolate atmosphere.

Toward Prediction of the Arctic System

predicting future states of the arctic system
on seasonal-to-century time scales
by integrating observations,
process research, modeling,
and assessment



arctic, *adj.* 1. of, at, or near the North Pole.
2. characteristic of the weather at or near the North Pole; frigid; bleak.
3. the region lying north of the Arctic Circle. (Random House).

Note: Other definitions extend the Arctic to the treeline, to the extent of pack ice, or to permafrost boundaries, to 60° North latitude, or to other political or natural limits.

system, *n.* 1. an assemblage or combination of things or parts forming a complex or unitary whole. (Random House).

science, *n.* 1. a branch of knowledge or study dealing with a body of facts or truths systematically arranged and showing the operation of general laws. (Random House).

Arctic System Science, *n.* 1. Systematic knowledge derived from observation, study, and experimentation carried on in order to determine the nature of the north polar regions as a connected unity.

Front cover: The snow of the Arctic is constantly on the move, being blown about by the incessant wind. Deposition and erosion of snow grains at the snow surface produces a beautiful and constantly changing pattern of sculpted drift forms known as sastrugi. Photo by Matthew Sturm.

Toward Prediction of the Arctic System

Predicting future states of the arctic system
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A science plan for the
National Science Foundation
Arctic System Science (ARCSS) Program



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Foreword

By the mid-1980s concern about the importance and sensitivity of the polar regions in a changing global environment led to several recommendations by the U.S. Arctic Research Commission and the Polar Research Board for increased scientific research aimed at understanding the Arctic in the context of climate, other global changes, and human activities. In 1987 two international workshops and a subsequent report, *Arctic Interactions* (1988), outlined a program of arctic research for emphasis in the International Geosphere-Biosphere Programme (IGBP). This report concentrated on a selected number of critical questions in interdisciplinary arctic science, the answers to which are expected to provide fundamental knowledge that will serve as a basis for assessing likely global changes in the next hundred years.

Building on this groundwork by the science community, the National Science Foundation (NSF) created in 1989 the Arctic System Science (ARCSS) Program as part of its contribution to the U.S. Global Change Research Program. The objectives of the research initiatives within the ARCSS Program were developed by the science community. The ARCSS Program has, almost since its inception, included both paleoenvironmental studies and studies of contemporary processes. In recent years, the ARCSS Program has emphasized research that illuminates the role of the Arctic in the global system through synthesis, integration, and modeling or that brings multidisciplinary perspective to bear on a particular problem in a particular land or seascape over a specified period of time. The investigation through the ARCSS Program of linkages between the arctic biophysical realms and the interaction of humans with the arctic system has become an increasingly high priority as well.

Because of the focus on system science and the need for ongoing collaboration and coordination, the scientific community recommended that NSF establish an ARCSS Program Office and a committee to coordinate the activities of the components and to facilitate their integration. At NSF's request, the ARCSS Program Office was established at the Arctic Research Consortium of the United States (ARCUS) and the first ARCSS Committee was appointed in 1991. The Committee comprises investigators participating in ARCSS research and others, not involved with ARCSS, who bring broader scientific viewpoints and expertise. Members of the committee serve three-year terms, allowing for changes in perspective and priorities as the research program matures. Each of the major programs and projects of the ARCSS Program have separate science steering and management structures.

In 1993, the ARCSS Committee prepared the first ARCSS Program science plan, *Arctic System Science: A Plan for Integration* (1993), which considered planning and activities already accomplished and recommended future priorities. The first science plan was intended to be updated as projects were initiated, research findings considered, and new needs emerged.

Foreword

Now, the ARCSS Committee has prepared the Program's second science plan, *Toward Prediction of the Arctic System: predicting future states of the arctic system on seasonal-to-century time scales by integrating observations, process research, modeling, and assessment*. This plan, begun under the leadership of W. Berry Lyons, former chair of the ARCSS Committee, examines the progress made in the last eight years, reviews significant research findings from each of the major programs of ARCSS, argues for the importance of increased integration and synthesis, and begins to define the questions and research priorities that now arise based on our increased understanding of the arctic system. As with the first plan, *Toward Prediction of the Arctic System* will evolve as the ARCSS Program matures, as questions are answered, as new connections among aspects of the arctic system become clear, and as our comprehension of global change and the arctic system expands.

On behalf of the ARCSS Committee, I would like to acknowledge the many contributions from the community of ARCSS researchers that have improved each successive draft of this plan. Appreciation is extended to those researchers who contributed data, figures, and photographs to enhance the plan and make it more meaningful. I was honored to join Knut Aagaard, Terry Chapin, Manda Lynch, Berry Lyons, Paul Mayewski, Jonathon Overpeck, and Bruce Peterson on the working group that developed the underlying approach to this integrative plan and prepared the first draft—special recognition is merited for their hard work, excellent representation of their respective communities, and the synthetic perspectives they brought to the task. The staff of ARCUS were essential to the successful production of the document. We would like to thank Wendy Warnick for her guidance of the planning and editorial process, Alison York and Marty Peale for their editorial skills, Kristjan Bregendahl for development of the publication layout and design, and Diane Wallace, Anne Sudkamp, and Milo Sharp for their editorial and technical assistance. Finally, on behalf of the arctic research community, the ARCSS Committee wishes to thank the National Science Foundation for the opportunity to participate in this planning process. We look forward to the ongoing implementation of ARCSS research priorities and to the fruits of all of our labors.

Jack Kruse, Chair
ARCSS Committee
March 1998

The Arctic in a Global Context

The primary objective of the U.S. Global Change Research Program (USGCRP) is to improve documentation, understanding, and prediction of the behavior of the Earth system. The goal is to develop reliable scientific projections upon which sound policy strategies and responses can be based.

Increasing atmospheric concentrations of greenhouse gases, due in part to the burning of fossil fuels, may significantly alter our climate. Land-use practices, industrial activities, waste disposal, transportation, and fisheries practices have altered terrestrial and marine ecosystems, thus affecting biological productivity, water resources, and the chemistry of the global atmosphere. These fundamental changes, evident also in the decline of stratospheric ozone and in acid precipitation, transcend traditional boundaries of scientific disciplines and drive the development and support of the USGCRP.

The objectives of the USGCRP are:

- ⌘ To establish an integrated, comprehensive, long-term program of documenting the Earth system on a global scale.
- ⌘ To conduct a program of focused studies to improve understanding of the physical, geological, chemical, biological, and social processes that influence the Earth system and that govern temporal trends of important variables on global and regional scales.
- ⌘ To develop integrated conceptual and predictive Earth system models.
- ⌘ To carry out integrated assessments.

The National Science Foundation's Arctic System Science (ARCSS) Program principally focuses on the response of the Arctic to global climate change forcings (*e.g.*, increased greenhouse gases) and processes unique to the Arctic that feed back to the global system thereby potentially enhancing or dampening larger scale climate forcings. For example, results from coupled models based on doubled atmospheric CO₂ indicate that there will be a net, globally averaged warming, which will be most pronounced in the northern polar regions. Our knowledge of arctic processes and our ability to model them, however, are currently insufficient to evaluate the accuracy of such models.

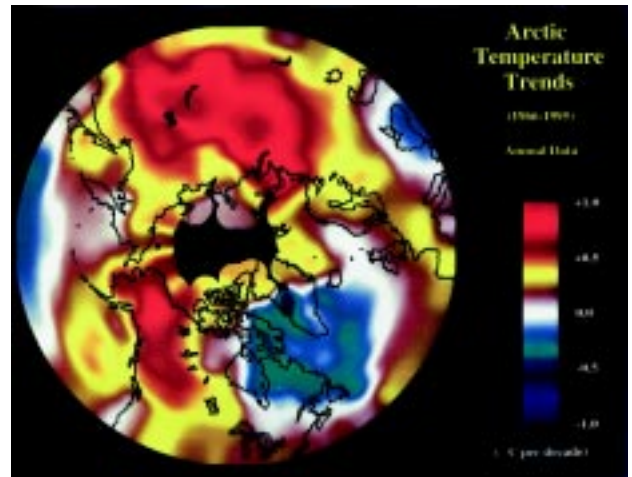


Figure 1. Observed trends of arctic winter mean temperatures from 1966–1995. Temperatures in northern North America are as much as 1–2°C warmer over the three decades (Chapman and Walsh 1993, updated).

The Global Context

Climate change forcings in the Arctic have important regional effects as well (*e.g.*, vegetation change, coastal erosion). These regional effects need to be understood in the context of other forcing mechanisms. Among these other mechanisms are large-scale human activities (*e.g.*, offshore petroleum development, long-range transport of contaminants).

The Arctic is a crucial region for studying global change. Sensitive indicators of change are reflected in its biota and snow and ice features, and short- and long-term climatic and atmospheric records are stored in permafrost, ice sheets, and lake and ocean sediments. The Arctic also affects global climate directly through strong feedback processes and through interactions among its atmosphere, ice cover, land surface, and ocean.

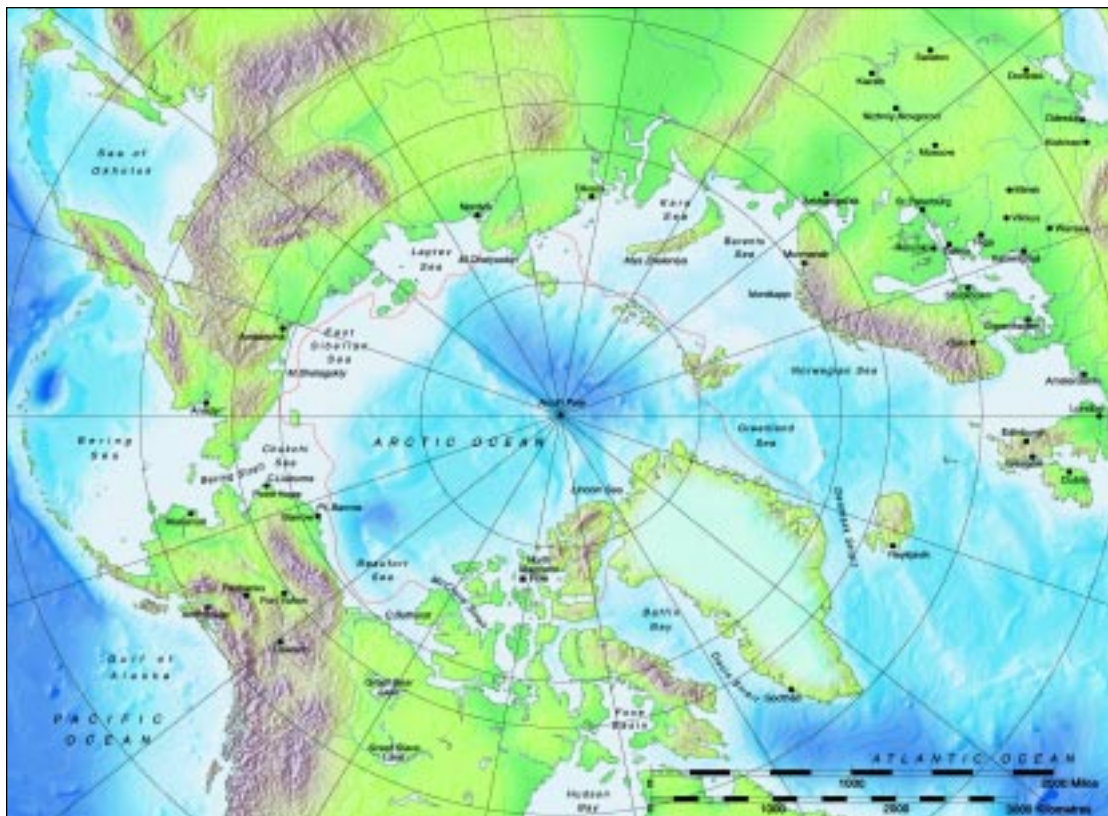


Figure 2. The Arctic Region, including physical features and place names; seasonal ice extent is indicated by red contour. Map from Mountain High Maps, © Digital Wisdom 1997.

The Arctic System Science (ARCSS) Program

The ARCSS Program

The Scientific Goals of the ARCSS Program

Accurately predicting the responses of physical, biological, and social systems within the Arctic to future global changes is the central theme of the ARCSS Program. The goals of the Program are:

- 1 to understand the physical, geological, chemical, biological, and social processes of the arctic system that interact with the total Earth system and thus contribute to or are influenced by global change, in order
- 2 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 changes on human beings and societal support systems.

While the major emphasis of ARCSS research has been the examination of links between arctic and global systems, both modern and paleoenvironmental studies indicate that the Arctic demonstrates strong regional responses to large-scale controls. For example, studies of meteorological records from Alaska and northeastern Siberia show that today's climates vary significantly on either side of the Bering Strait (Mock *et al.* N.d.). This spatial heterogeneity, resulting from variations in synoptic-level atmospheric circulation patterns, has characterized the Beringian region for at least the last 130,000 years. Such climatic variations have had major influences on landscape development. For example, the major post-glacial spread of coniferous forest occurred approximately 2,000 years later in Alaska than in northeastern Siberia during the period of global warming that followed the late Pleistocene ice age (Lozhkin *et al.* 1993). Northern marine environments are equally sensitive as illustrated by the strong control of the annual radiation balance over sea-ice distribution and duration, with consequent impacts on marine transportation, animal migration routes, and subsistence activities of Native peoples.



Above. Walrus on the sea ice, five miles from Barrow, Alaska. Photo © Bill Hess, Running Dog Publications.

Below. Muskoxen in northeastern Greenland. The muskox is highly adapted to life in the Arctic and is indigenous to northeastern Greenland, Canada, and Alaska. Photo by Henning Thing.

The ARCSS Program

The areal extent and thickness of seasonal snow cover, sea ice, permafrost, glaciers, and river and lake ice are all expected eventually to decrease as the climate warms. Initially, warming may generate more precipitation and result in thicker snow cover and increased glaciation; as warming continues, however, ablation is likely to exceed accumulation, as already observed on Alaskan glaciers. These changes in snow and ice will, in turn, affect the distinct fauna and flora of arctic ecosystems. For example, increased snow depths, earlier spring snowmelts, and increased frequency of icing and crusting events may significantly decrease caribou populations.

Global changes of significance to the Arctic are not limited to climate. For example, resource development is a potential source of both environmental change and economic activity—increasing access to the Arctic is likely to exert pressure on arctic ecosystems while providing expanded sources of income for residents. Long-range transport of persistent organic compounds to the Arctic leads to contamination of marine mammals consumed by indigenous populations.

The ARCSS Program seeks to understand climate effects in the context of other potentially important forces for change. The Program cannot by itself, however, fully address the concerns of arctic peoples about such forces for change as offshore development and contaminants in subsistence foods. These important topics require additional investments in research in partnership with arctic communities and other federal and state programs.

Over the eight-year history of the ARCSS Program, principal areas of activity have included:

- ⌘ observations of changes in the arctic system thought to be important to climate change, including the state of the atmosphere, ocean, and sea ice; the surface budgets of energy, moisture, and chemical constituents (*e.g.*, CO₂ and CH₄); and the radiative properties of elements of the arctic system;
- ⌘ studies of arctic system processes that may produce significant feedbacks to the global system;
- ⌘ development of models based on process studies to predict the consequences of global change for the arctic environment and to predict the global consequences of changes occurring within the Arctic;
- ⌘ compilation of a record—from cores of ice sheets and from lake, estuarine, and marine sediments—of past environmental (especially climatic) variability, including regional variability; and
- ⌘ coupling of paleoclimatic and modern observational records to improve quantitative reconstructions of past conditions for better evaluation of modeling results.

The ARCSS Program

ARCSS Objectives

An early emphasis in ARCSS research has been understanding arctic climate and the effects of climate change on the biogeochemical cycles and components of the arctic system. While this emphasis will remain vital, it is only one of the four scientific aims of ARCSS. The ARCSS Program will develop a better understanding of:

- ⌘ processes and mechanisms of change in the arctic climate system and its range of natural variability,
- ⌘ the role of the Arctic in global biogeochemical cycling,
- ⌘ the structure, function, and stability of arctic ecosystems, and
- ⌘ the links between global change and human activity in the Arctic.

During the next five years, the major goals of ARCSS will be addressed through the following general objectives:

- ① Develop a comprehensive understanding of past environmental variability in the Arctic through documentation of past changes and assessment of possible mechanisms responsible for the observed variations;
- ② Expand the scale of predictive environmental assessments from the regional to the circumpolar;
- ③ Incorporate our knowledge into predictive models of climate and environmental change in the Arctic;
- ④ Integrate our knowledge of the arctic system into models of global and regional change; and
- ⑤ Validate these models with observations of past climate changes and with studies of processes that have large effects on climate feedbacks.

The two examples below illustrate how these general objectives, when integrated, could produce meaningful predictions of the behavior of the arctic system:

- ⌘ Modeling freshwater and nutrient inputs to arctic marine ecosystems to assess effects on the larger marine ecosystem, as well as ocean circulation, human resource use, and climate change;
- ⌘ Evaluating climate changes' affects on arctic marine and terrestrial ecosystems and on northern communities in conjunction with other environmental changes such as resource development, increasing access to the Arctic, and contaminants.

In September 1986, the sea ice at Barrow, Alaska drifted far from shore; three severe storms in rapid succession raised unusually high surf, which the ice normally constrains. The third storm broke the bluff facing the ocean in Barrow, exposing the permafrost, and left a house dangling over the sea; the house had to be moved by crane to save it. Photo © Bill Hess, Running Dog Publications.



Significant Research and Findings of the ARCSS Program

An integrative and synthetic approach is required for realistic understanding of the arctic system because of:

- ⌘ the region's physical and biological complexity,
- ⌘ the need to incorporate information about arctic resources such as fisheries and petroleum reserves, and
- ⌘ the requisite assessments of human responses to change.

Unifying questions that drive ARCSS research are shown in Table 1 in the following foldout, with examples of ARCSS-funded observational and process studies that address these questions. Observational studies and investigations of specific mechanisms, feedbacks, and cycles provide a basis for the development of models, as noted in figures 3–5 and 9. Modeling is necessary for predicting the behavior of the arctic system, impacts of change on regional and global scales, effects of change on planning and policies, and effects of policies on change.

Table 1 suggests how appropriate economic and policy responses to the issue of global change in the Arctic might be achieved. Both paleoclimatic observational records and global climate system models quantify the importance of the Arctic within the Earth system, documenting that cryospheric processes in the Arctic amplify the signals of global climate change. The ARCSS Program has built upon these forms of research by evaluating the specific impacts of global system changes on arctic processes, feedbacks, and cycles. These impacts have further ramifications on specific resources (*e.g.*, caribou migration routes, access to petroleum reserves). A more complete understanding of such first- and second-order effects, extended from local to circumarctic and global impacts, will significantly influence development of specific policies concerned with public health, subsistence lifestyles, environmental management, and many other important issues.

An understanding of spatial and temporal scales of variability and ecosystem response can be achieved only through a synthesis of existing information and new observations. The role of arctic peoples in system change is an important new aspect of the ARCSS Program—models will be strengthened with new data for input and verification, and assessment of impacts and responses will reflect the use of physical, biological, and geochemical data and their relevance to the future human condition in the Arctic.

Table 1. This table shows the major questions being addressed through ARCSS Program research, the research approaches necessary to achieve an understanding of the arctic system through synthesis and integration across temporal and spatial scales, and the use of assessment to formulate appropriate economic and policy responses to the issue of global change in the Arctic. The research “bullets” included in the table are examples of research conducted by the ARCSS Program in the relevant categories; the table is not meant to provide a comprehensive listing of ARCSS research.

Key questions in Arctic System Science	What is the role of the Arctic in the global system (past, present, and future)?	What are the types and sources of global change in the Arctic?	What are the effects of changes on climate, chemistry, ecosystems, and humans?
Observations	<ul style="list-style-type: none"> ⌘ Climate is sensitive to variations in sea-ice and glacial extent, and <i>vice versa</i> (Figures 3, 4, and 5). 	<ul style="list-style-type: none"> ⌘ Rapid climate shifts (Figure 6) ⌘ Greenhouse warming ⌘ Contemporary observations (<i>e.g.</i>, permafrost, trace-gas fluxes, climate) ⌘ Observations from paleoenvironmental research (<i>e.g.</i>, proxy climate and trace-gas data from ice cores and sediment cores) 	<p>Changes in:</p> <ul style="list-style-type: none"> ⌘ Permafrost (Figure 7) ⌘ Wetlands ⌘ Vegetation (<i>e.g.</i>, treelines) ⌘ Available resources (<i>e.g.</i>, fisheries, mammals, forestry) ⌘ Sea ice ⌘ Changes in harvest of marine mammals ⌘ Changes in climate variability (<i>e.g.</i>, storm frequency and locations)
Process	<ul style="list-style-type: none"> ⌘ Ice-albedo feedback ⌘ Freshwater flux (Figure 8) ⌘ Snow-albedo feedback ⌘ Regional vegetation feedbacks 	<ul style="list-style-type: none"> ⌘ Changes in thermohaline circulation ⌘ Changes in atmospheric composition ⌘ Changes in the hydrological cycle ⌘ Biogeochemical mechanisms for release of methane and carbon dioxide ⌘ Changes in populations of plants, animals, and humans ⌘ Solar variability ⌘ Volcanic activity 	<ul style="list-style-type: none"> ⌘ Surface and subsurface hydrology (Figure 9) ⌘ Terrestrial and marine ecosystem dynamics ⌘ Atmosphere dynamics, cloud processes ⌘ Migration decisions of northern populations
Modeling	<ul style="list-style-type: none"> ⌘ “Polar amplification” in general circulation models 	<ul style="list-style-type: none"> ⌘ Test model ability to simulate changes using paleo data (Figure 10) ⌘ Terrestrial ecosystem models (Figure 11) ⌘ General circulation models (GCM) and regional climate models (RCM) ⌘ Carbon cycle ⌘ Watersheds 	<ul style="list-style-type: none"> ⌘ Long-term accurate prediction ⌘ High-resolution numerical weather prediction (NWP) ⌘ Representation of climate variability ⌘ Sustainability of arctic human settlements
Assessment	<ul style="list-style-type: none"> ⌘ Global thermohaline circulation ⌘ Arctic magnifies global circulation ⌘ Arctic acts as sink in global energy budget 	<p>The effects of:</p> <ul style="list-style-type: none"> ⌘ increased climate variability on terrestrial and marine resources ⌘ decreased sea-ice extent on marine transportation ⌘ sea-level rise on northern communities 	<p>The effects of change on:</p> <ul style="list-style-type: none"> ⌘ availability of subsistence resources (Figure 12) ⌘ economic development ⌘ the Earth’s environment (Figure 13)

Observations. Observational work provides an essential empirical foundation for research in arctic system science; long-term observations are particularly crucial in detecting global change. Figures below exemplify observational studies which address important fundamental questions and provide a basis for modeling and assessment of global change in the arctic system.

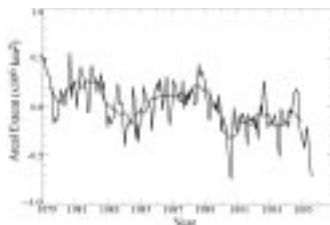


Figure 3. Time series of sea-ice extent anomalies (monthly means and 12-month running means are shown) estimated from passive microwave data from the stippled area in Figure 4.



Figure 4. Comparison of the extent of the September perennial ice cover in 1990–95 (medium gray area) and 1979–89 (dark gray area). The dark gray area indicates the portion of the Arctic Ocean that was ice-free in 1990–95. This reduction in the ice cover accounts for most of the below-normal ice extent seen in 1990–95 in Figure 3.



Figure 5. Mean ice motion for May–July 1990 as simulated using a dynamic-thermodynamic ice model forced by National Center for Environmental Prediction, winds, air temperatures, and downwelling radiation. Note the strong northward ice transport in the Siberian sector of the Arctic that contributes to reduced sea-ice extent. Figures courtesy of James Maslanik.

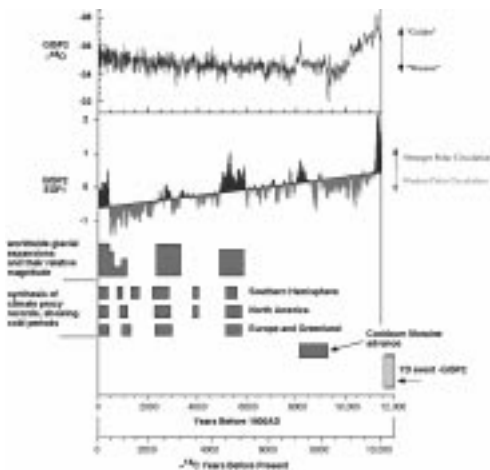


Figure 6. Holocene variability from ARCSS/GISP2 compared to other paleo-proxy records. Holocene climate is characterized by rapid climate-change events and considerable complexity. GISP2 Holocene $\delta^{18}\text{O}$ (proxy for temperature) (Grootes et al. 1993) and EOF1 (composite measure of major chemistry representing atmospheric circulation) show parallel behavior for the Early Holocene but not for the Late Holocene (O'Brien et al. 1995). Worldwide glacier expansions and syntheses of various climate proxy records from Europe, Greenland, North America, and the Southern Hemisphere show cold periods (Andrews and Ives 1972; Denton and Karlen 1973; Harvey 1980) that match the GISP2 EOF1 (atmospheric circulation).

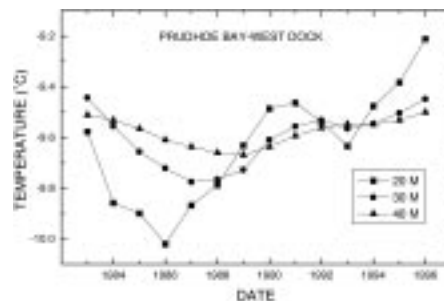


Figure 7. Time series of temperature measurements at West Dock near Prudhoe Bay, Alaska showing warming that has occurred since 1986. The ground surface temperature must have warmed more than 4°C to have produced this warming at depth. Figure courtesy of Thomas Osterkamp.

Process. Process studies seek to understand, at a variety of temporal and spatial scales, the mechanisms affecting the operation and the response of a system—be it a biological or physical system. As the scales and the number of elements comprising a system increase, interactions among processes are more complicated and predictions of system evolution become more uncertain. A firm understanding of the relevant processes eventually will lead to greater confidence in predictions and understanding of the system. Process studies are conducted within laboratories and in the field (at scales ranging from small plots of a few meters to many hundreds of kilometers), and are often tied to a simple analytical or numerical model. Small-scale studies often lead to “predictive laws” and isolate system descriptors—easily measured by broad field surveys, remotely sensed data sets, and/or routinely monitored variables—that can then be extrapolated to larger scales. At right and below are results from process studies conducted under the ARCSS Program.

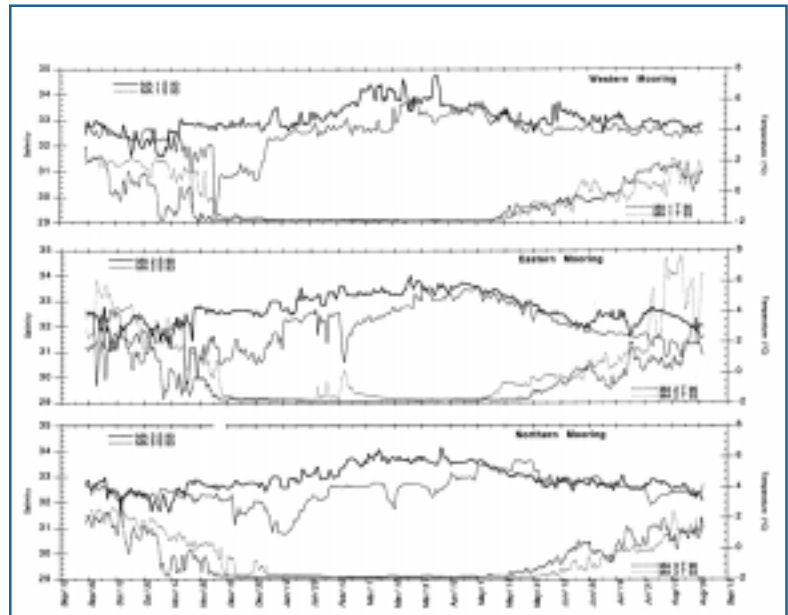


Figure 8. Freshwater flux through Bering Strait is an important element of the global freshwater cycle. This flux depends upon the volume transport and salinity of water flowing through the strait. This figure shows temperature (dashed) and salinity (solid) time series for 1990–1991 (heavy lines) and 1993–1994 (lighter lines). Maximum salinity occurs in March–April each year and reflects salt rejection from ice growth on the Bering shelf. Low-salinity water enters the Arctic Ocean mixed layer while more saline waters ventilate deeper layers. The annual cycle and interannual differences are related to ice production and the sources of Pacific Ocean water which feed Bering Strait. Figure from Roach et al. (1995).

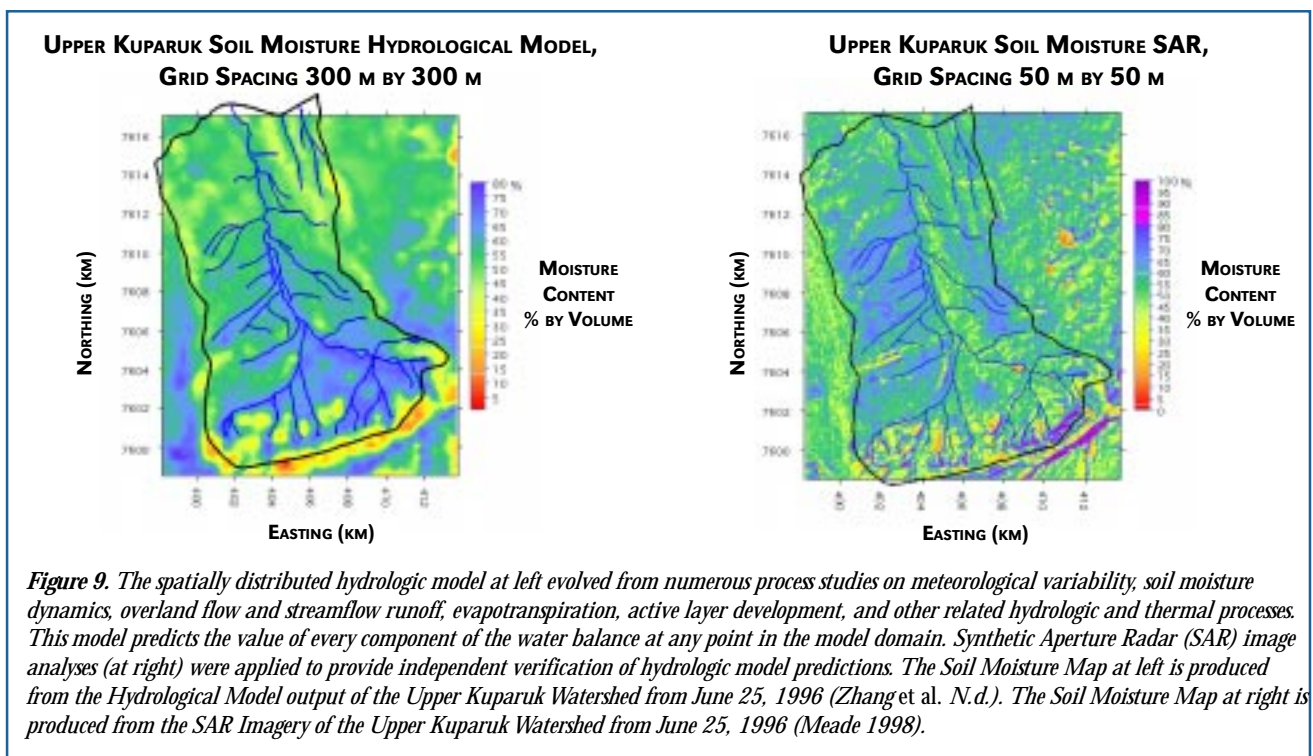


Figure 9. The spatially distributed hydrologic model at left evolved from numerous process studies on meteorological variability, soil moisture dynamics, overland flow and streamflow runoff, evapotranspiration, active layer development, and other related hydrologic and thermal processes. This model predicts the value of every component of the water balance at any point in the model domain. Synthetic Aperture Radar (SAR) image analyses (at right) were applied to provide independent verification of hydrologic model predictions. The Soil Moisture Map at left is produced from the Hydrological Model output of the Upper Kuparuk Watershed from June 25, 1996 (Zhang et al. N.d.). The Soil Moisture Map at right is produced from the SAR Imagery of the Upper Kuparuk Watershed from June 25, 1996 (Meade 1998).

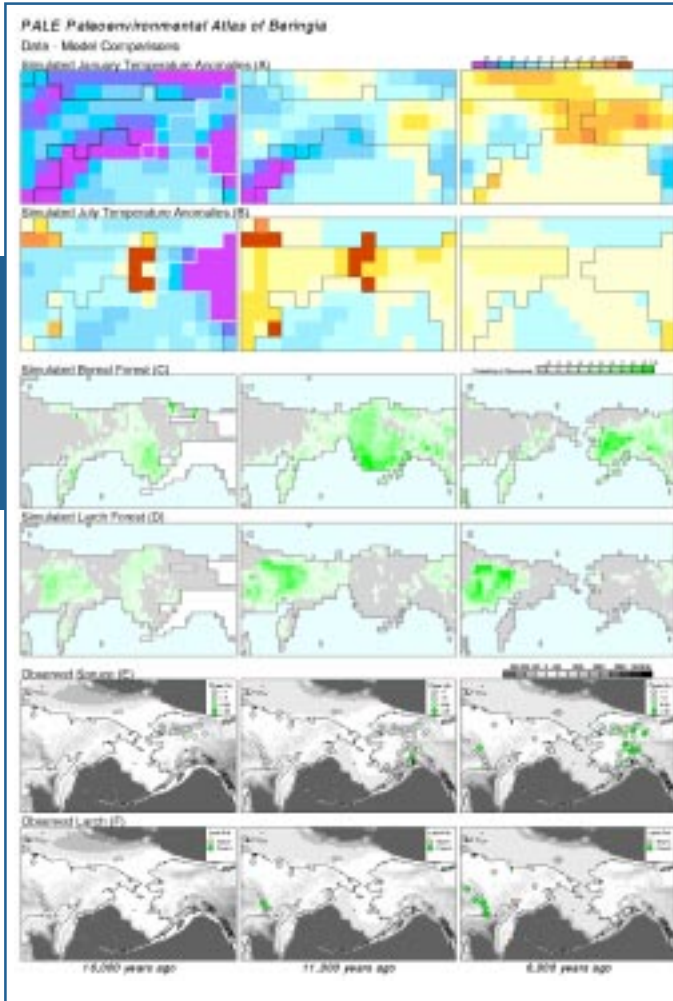


Figure 10. The top two sets of maps show simulated January and July temperatures for 16,000, 11,000, and 6,000 (calendar) years before present, from the NCAR (National Center for Atmospheric Research) CCM 1 (Community Climate Model). The maps reveal an unexpected “early” response of summer temperature in Beringia to deglaciation and greater-than-present-summer-time solar radiation, with near-modern temperatures being reached in some regions by 16,000 years before present. The implication of this early warming may be seen in the middle sets of maps, which show the simulated probability of occurrence of boreal forest and larch forest (Matthews 1983), on a 1-degree-by-1-degree grid using ecological response surfaces (Prentice et al. 1991) and the climate-model output. The simulated distributions of spruce forest and larch forest can be compared with the observed distributions shown on the bottom sets of maps, drawn using data from the PALEVirtual Atlas of paleoenvironmental data from Beringia (PALE Beringian Working Group 1998). The maps show the tendency for the simulated distribution of these vegetation types to be more widespread than the observed, and Bartlein et al. (1998) have ascribed these differences to aspects of the simulated atmospheric circulation in the model. Figure provided by Patrick Bartlein.

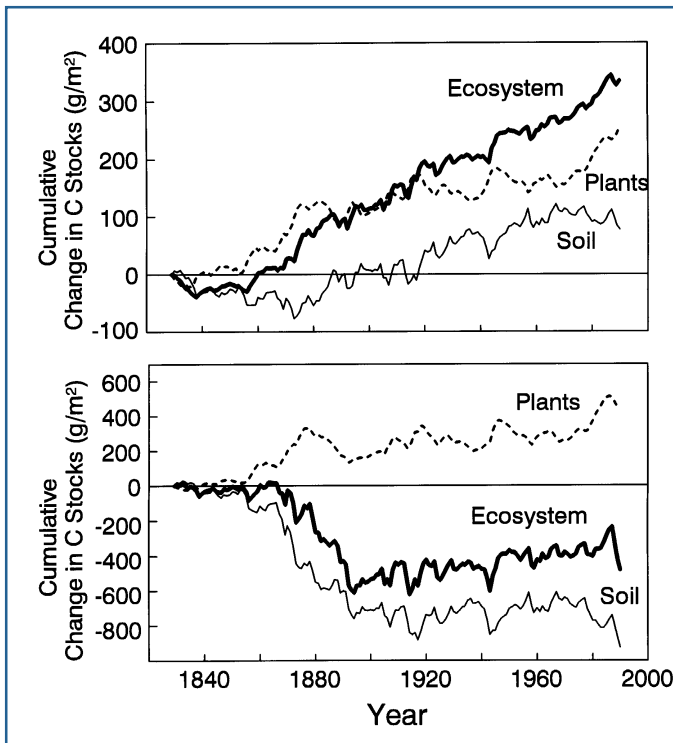


Figure 11. Reconstructed cumulative changes in carbon stocks in Alaskan tussock tundra using the Marine Biological Laboratory’s General Ecosystem Model (MBL-GEM). Reconstructions were made using estimated carbon dioxide and temperature records and assuming constant, present-day soil moisture (upper figure) or soil moisture that decreased as climate warmed during the latter half of the 19th century. The cause of increased carbon storage in plants is a temperature- or a temperature-and-moisture-induced increase in nitrogen turnover in soils. With constant moisture, this increased productivity results in higher litter inputs to soil and an eventual buildup of soil organic matter. With drier soils, litter inputs to soils do not keep up with the temperature-and-moisture-induced increases in soil-carbon losses. Carbon-nutrient-water interactions are clearly important to the carbon balance of arctic terrestrial ecosystems. Figure redrawn from McKane et al. (In press).

Modeling. Models are an important means to better understand the arctic system, predict the response of the Arctic to environmental change, and to test policy scenarios and resulting responses. Modeling is being used in many ways in the ARCSS Program (facing page); most ARCSS projects have included a modeling effort—based on information from observational and process studies—from their inception (*Modeling the Arctic System* 1997). Examples of ARCSS modeling efforts include work linking modeling with remote sensing to allow extrapolation of field measurements to large scales, using paleoenvironmental proxy climate data to test model ability to simulate changes, and models of animal population dynamics in response to perturbations.

Assessment. Assessment is an important step in determining the implications of basic research for people's well-being. This step is essential to policy and management decision making. Regional assessments of global change impacts provide an important means of interdisciplinary analysis and integration; they are a high priority on the agendas of many U.S. and international research programs. Although assessments related to particular problems are occurring, no comprehensive integrated regional impact assessment has been undertaken of the Arctic to date. Assessment is essential to meet the second goal of the ARCSS Program (page 3), formulating policy options in response to anticipated impacts of climate change.

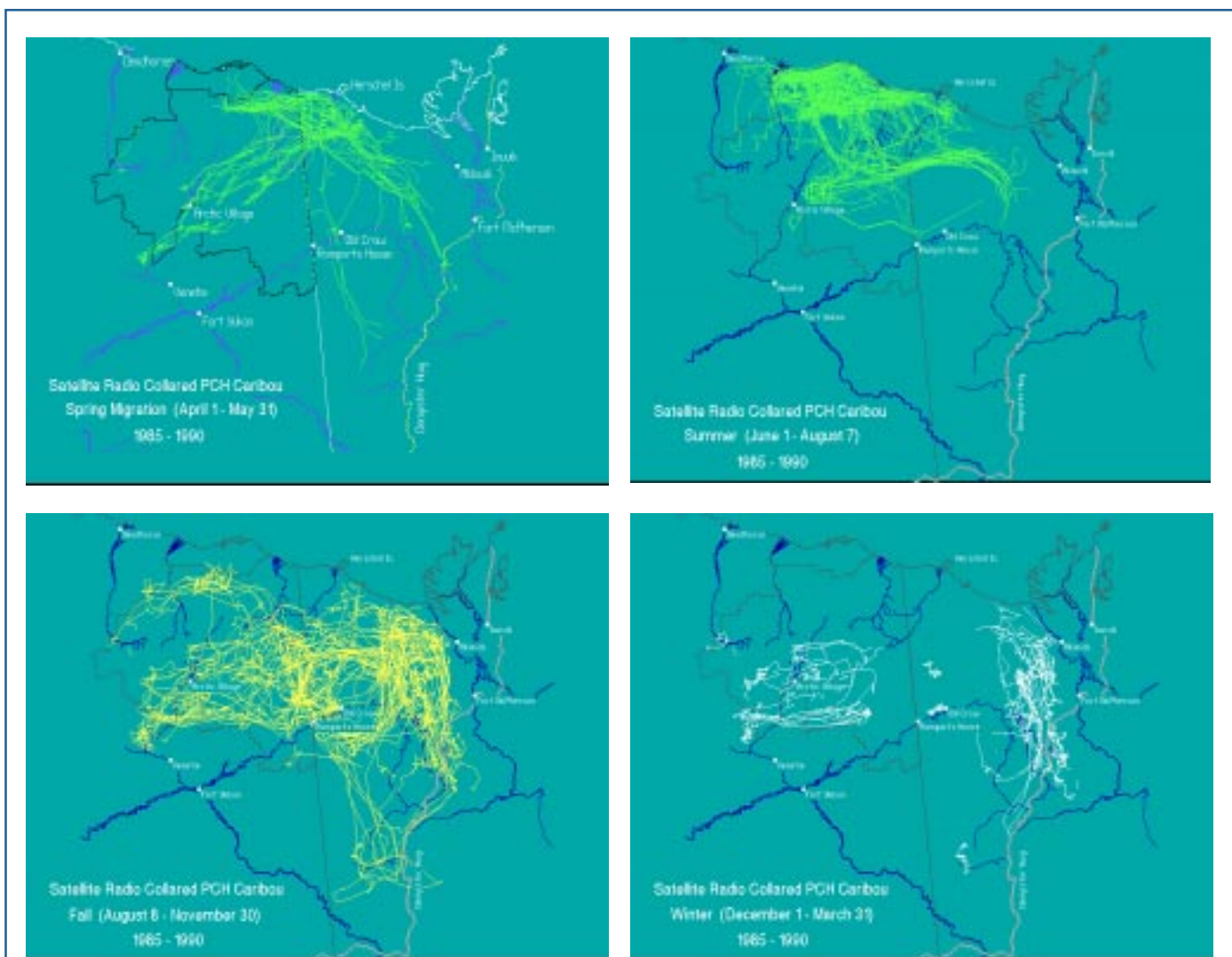


Figure 12. The figures above show seasonal caribou migration on the North Slope of Alaska. Tracking satellite-collared caribou illustrates variations in caribou movements. Climate change may affect caribou movements and, as a result, affect the availability of caribou, an important subsistence resource for northern communities. Figures courtesy of Brad Griffith.

Assessment and global perspectives. The figure below shows several components of global change. A recent synthesis report from the International Geosphere-Biosphere Programme (Walker and Steffen 1997), from which this figure is taken, says *“The accelerating changes to the Earth’s environment are being driven by growth in the human population, by the increasing level of resource consumption by human societies and by changes in technology and socio-political organizations.”* ARCSS Program research is being conducted in the context of the types of global change research illustrated here.

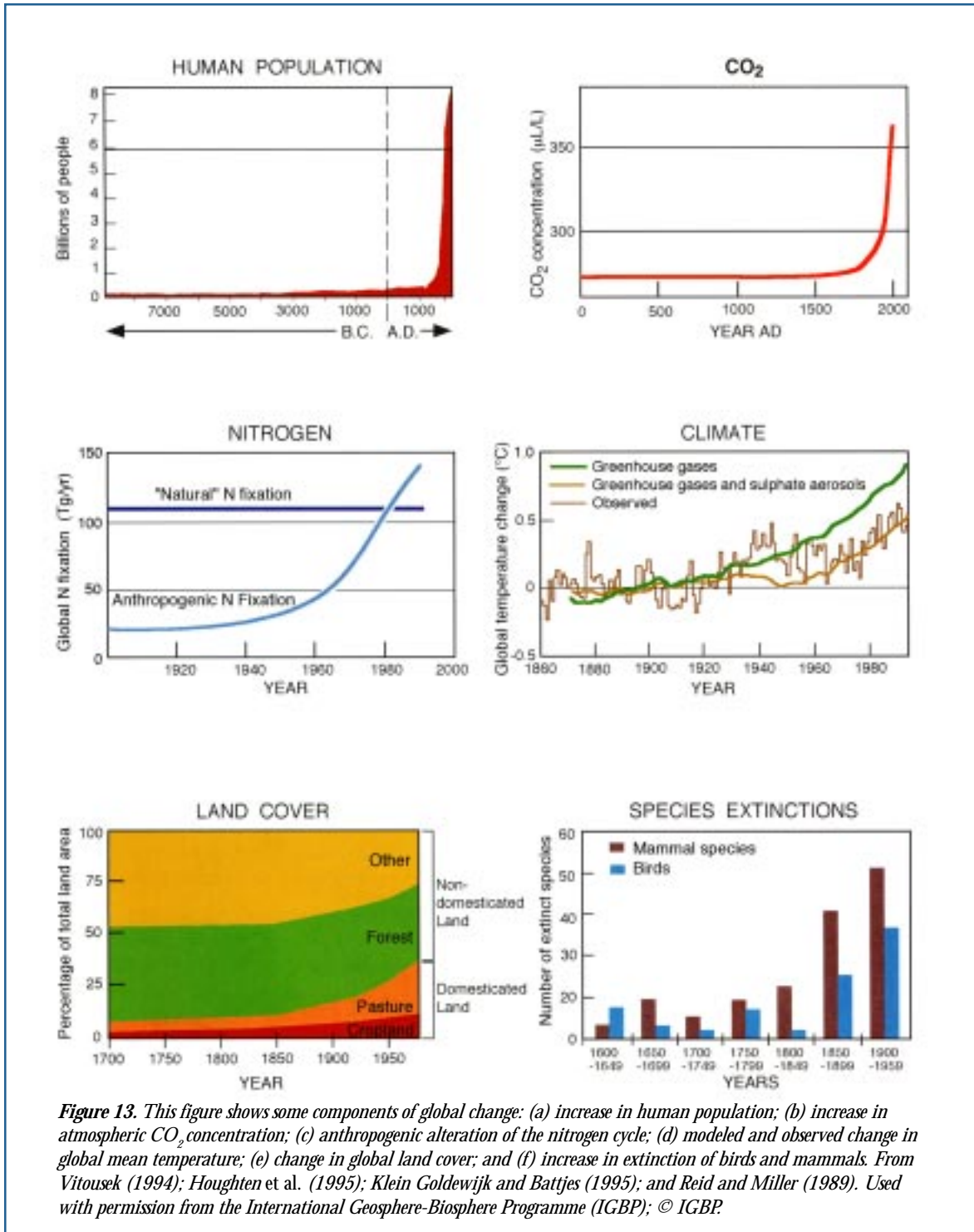


Figure 13. This figure shows some components of global change: (a) increase in human population; (b) increase in atmospheric CO₂ concentration; (c) anthropogenic alteration of the nitrogen cycle; (d) modeled and observed change in global mean temperature; (e) change in global land cover; and (f) increase in extinction of birds and mammals. From Vitousek (1994); Houghten et al. (1995); Klein Goldewijk and Battjes (1995); and Reid and Miller (1989). Used with permission from the International Geosphere-Biosphere Programme (IGBP); © IGBP.

Implementation of ARCSS Program Research

ARCSS Program research projects have been implemented in several phases over the past eight years (Appendix, pages 40–41). The field-intensive phase of GISP2, the first project implemented, is now complete. New initiatives in several areas of ARCSS research are under development. A brief description of the primary components and major research programs in the ARCSS Program follows. Priorities within ARCSS have been established on the basis of:

- ⌘ the potential impact of research on a given topic,
- ⌘ relevance to global change, and
- ⌘ the extent to which a project addressed major gaps in current knowledge.

Integration and synthesis are considered to be the highest general priorities of ARCSS; efforts bridging the various components will be emphasized, both scientifically and programmatically, as ARCSS evolves. Results from integration studies are likely to indicate data gaps and needs for future research on presently understudied problems.

ARCSS Program Components

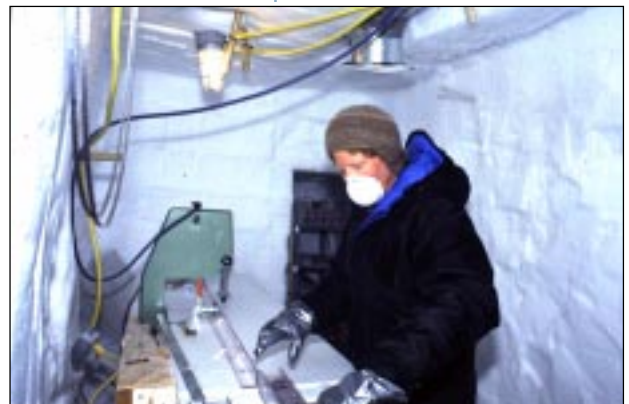
Paleoenvironmental Studies

Greenland Ice Sheet Project Two (GISP2)

In July 1993, the Greenland Ice Sheet Project Two (GISP2) successfully completed drilling to the base of the Greenland Ice Sheet in central Greenland (72.6° N; 38.5° W; 3200 m above sea level). GISP2 recovered a 3053.44 m ice core and penetrated 1.5 m into the underlying bedrock. In cooperation with its European companion project, the Greenland Ice Core Program (GRIP), GISP2 has developed the longest high-resolution paleoenvironmental record available from the northern hemisphere (more than 250,000 years). A comparison of electrical conductivity and oxygen isotope series between the GISP2 and GRIP cores (Grootes *et al.* 1993; Taylor *et al.* 1993) has revealed that at least the upper 90% (approximately 2800 m representing 110,000 years) display extremely similar, if not absolutely equivalent, records.

The remarkably precise dating of the GISP2 ice core (Alley *et al.* 1993, Sowers *et al.* 1993, Bender *et al.* 1994, Meese *et al.* 1994) and detailed and robust measures of the paleoenvironment (*e.g.*, gases, dissolved ions, stable isotopes, particles) provide a comprehensive framework for other paleoclimate records. To date, more than 150 peer-reviewed articles and *Greenland*

Researchers processed the ice core for on-site measurements and analysis in the GISP2 science trench at Summit, Greenland. Here, Mark Twickler from the University of New Hampshire sections a portion of the GISP2 ice core for analysis of chemical composition, particles, stable and cosmogenic isotopes, and laser light scattering. Special gloves and masks are used to prevent contamination of the pristine ice. Photo by Richard Alley.



ARCSS Program Research

Summit Ice Cores (Mayewski *et al.* 1997)—a special issue of the *Journal of Geophysical Research*—have been produced from the GISP2 record, covering a wide range of topics including site surveys, process studies, new innovations in analytical and statistical techniques, transfer function studies, comparisons with regional-to-global scale paleo-climate series, histories and implications of unique events (*e.g.*, volcanism, biomass burning, anthropogenic emissions), paleoenvironmental reconstructions, and social responses to climate change.

One of the most striking GISP2 results is verification that rapid climate-change events associated with rapid and massive reorganizations in the ocean-atmosphere system occurred at frequent intervals throughout at least the last glacial cycle (Figure 14). The largest events are characterized by changes in climate that are close to the order of glacial/interglacial cycles (Taylor *et al.* 1992, Alley *et al.* 1993, Mayewski *et al.* 1993, 1994ab, Cuffey *et al.* 1995). Perhaps most surprising is the evidence that at least some of these rapid climate transitions occur in less than two years and may persist for centuries to millennia.

Stimulated by these findings, investigators have shown that these events are globally distributed in ocean, atmosphere, and terrestrial paleo-

environments. Of greatest consequence to humans, however, is the evidence of these events during our current interglacial cycle, the Holocene (Meese *et al.* 1994, O'Brien *et al.* 1995; Figure 6).

The field-intensive component of GISP2 is complete; several new research activities are proceeding on the foundation of this successful endeavor, including:

- ⌘ higher resolution sampling of archived core segments to gain a more detailed understanding of specific events,
- ⌘ intensified climate and glaciological modeling efforts,
- ⌘ year-round atmospheric sampling at the GISP2 site to refine the air-snow transfer function relationship, and
- ⌘ comparison with other paleoenvironmental records (notably PALE), instrumental series, and archaeological records.

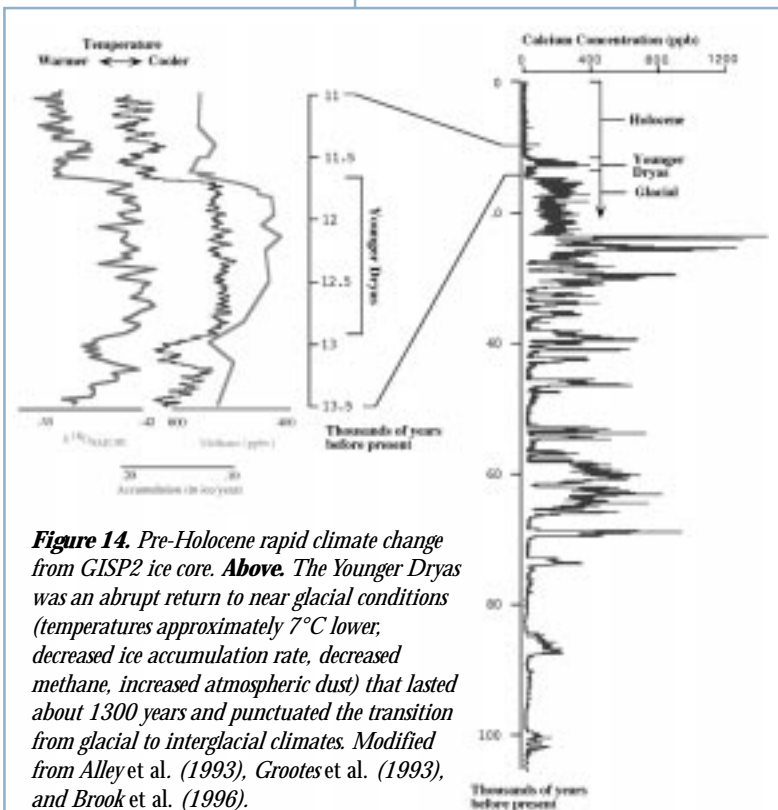


Figure 14. Pre-Holocene rapid climate change from GISP2 ice core. **Above.** The Younger Dryas was an abrupt return to near glacial conditions (temperatures approximately 7°C lower, decreased ice accumulation rate, decreased methane, increased atmospheric dust) that lasted about 1300 years and punctuated the transition from glacial to interglacial climates. Modified from Alley *et al.* (1993), Grootes *et al.* (1993), and Brook *et al.* (1996).

Right. This high-resolution calcium record from the GISP2 ice core indicates the relative amount of dust in the atmosphere over Greenland and thus documents other abrupt, frequent, and massive changes in climate that characterize the glacial portion of the ice-core record. Figure modified from Mayewski *et al.* (1993, 1994a).

Climatic events (*i.e.*, the Little Ice Age) vary in intensity and duration on a regional and/or hemispheric basis. To investigate regional variation, hemispheric or bipolar comparisons, or specific climate events (*e.g.*, Holocene and Eemian interglacials) in detail, several complementary ice-core efforts are ongoing or planned. In the Arctic, these ice-core activities have been organized into an initiative known as the International Circum-Arctic Paleoclimate Program (ICAPP) within Past Global Changes (PAGES) of the International Geosphere-Biosphere Programme (IGBP).

Paleoclimates of Arctic Lakes and Estuaries (PALE)

Paleoclimates of Arctic Lakes and Estuaries (PALE) investigations seek to describe the range of spatial and temporal variations in climate on interannual-to-millennial time scales, as indicated by proxies preserved in lacustrine and estuarine sediments, to improve understanding of changes in arctic climates. The primary scientific problems that guide this work are defining:

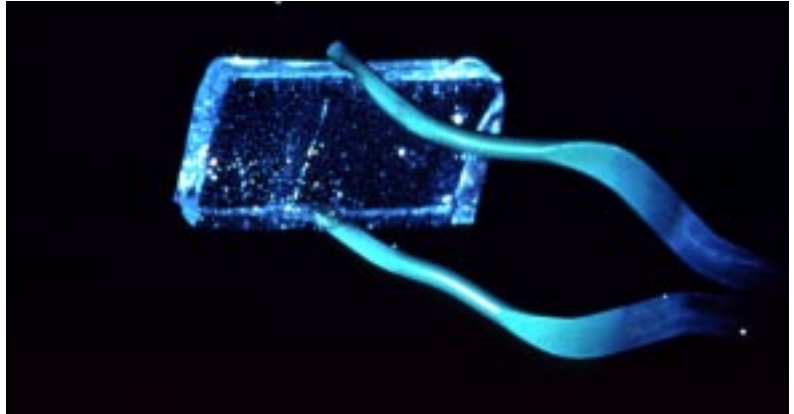
- ⌘ timing, rates, magnitudes, spatial patterns, and controls of arctic climate variability;
- ⌘ climate controls over glacier and ice-sheet inception, mass balance, variation, and recession; and
- ⌘ the role of the arctic climate system in the global system (*e.g.*, amplifying or stabilizing feedbacks to the global system).

To address these issues, PALE is acquiring a reliably dated network of sites where paleoclimate proxies (*e.g.*, pollen, diatoms, stable isotopes) are either:

- ⌘ calibrated quantitatively with modern data sets, or
- ⌘ assessed qualitatively through knowledge of key ecological and/or process relationships.

These proxies provide the basic record of late Quaternary environmental variations. The patterns described from the fossil data are then compared to atmospheric general circulation models or conceptual models of climate change, so that possible mechanisms and feedbacks responsible for the observed changes can be described. This coupled approach of documentation by the fossil data (*i.e.*, what happened) and explanation using data-model comparisons (*i.e.*, why it happened) is the core of PALE research.

PALE has sponsored research in Alaska, Iceland, Canada, and Russia and is currently taking a shared leadership role in Circum-Arctic PaleoEnvironments (CAPE), a PAGES project charged with synthesizing



A small section of GISP2 ice core being prepared for chemical analysis. On close inspection, air bubbles from the ancient atmosphere which are locked in the ice are visible. Photo by Michael Morrison.

ARCSS Program Research

major paleoclimatic and paleoenvironmental trends in the Arctic over the last 250,000 years. PALE is currently making key contributions to Paleoenvironmental Multiproxy Analysis and Mapping (PMAP), a global environmental PAGES project, by developing a virtual atlas of Beringia in which maps and time series of primary and value-added data (*e.g.*, paleovegetation, inferred climatic parameters) are available in interactive, online format (PALE Beringian Working Group 1998). Ultimately, this atlas will expand, documenting the spatial and temporal patterns of change during the late Quaternary throughout the Arctic. Such summaries will become the major means for evaluating atmospheric general circulation model simulations. In a related initiative, PALE researchers are testing climate model runs against both current and past (6,000 ka BP) climate data. PALE work with climate models will become increasingly important to LAII and OAII researchers as they enter the modeling stage. Modeling efforts have been supported through a PALE postdoctoral position at the National Center for Atmospheric Research (NCAR). Activities have furthered data-model comparisons, examined ice-sheet initiation and mass balance, and explored linkages of global vegetation models and climate models at both global and regional scales.

One of the most striking breakthroughs in PALE research has been pioneering work to quantify changes in climate, vegetation, and lake conditions over the last 1,000 years through analyses of annually resolved lake-sediment records (Figure 15; Hughen *et al.* 1996, Lamoureux and Bradley 1996, Overpeck *et al.* 1997). The work demonstrates that the arctic environment has been far from stable; rather it exhibits a large range of

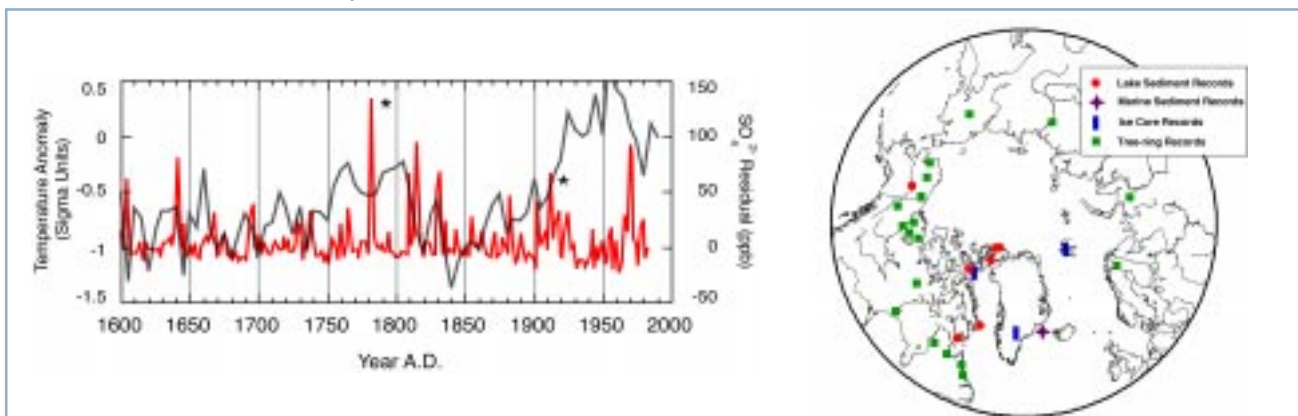


Figure 15. ARCSS paleoenvironmental research has expanded to utilize data from many proxy sources in order to understand the full range of arctic environmental variability. Most recently, annually resolved records from a circumarctic array of new and published sites (see map) were combined to yield the first reconstruction of circumarctic summer temperature variations over the last 400 years. This record clearly shows the arctic “Little Ice Age” prior to this century, as well as the dramatic warming that has occurred since the mid-19th century. A comparison of this temperature series (solid line; in z-score units) with the GISP2 volcanic sulfate record (red line) shows a clear relationship between volcanic aerosol forcing and five-year averaged summer temperature; cold periods correspond to higher volcanic activity. Asterisks indicate two volcanic events (Icelandic Laki of 1783 and Alaskan Katmai of 1912) that are overrepresented in the GISP2 record because of their proximity to Greenland. Also of note is the fact that 20th-century warmth is not necessarily the norm for the Arctic. Figures modified from Zielinski *et al.* (1994) and Overpeck *et al.* (1997).

decadal-scale climatic variability. Similarly the aquatic ecology of many lakes has changed dramatically over the last 150 years.

PALE regional syntheses have also been used in evaluating general circulation model (GCM) output, which is particularly important because these global models tend to simulate high-latitude climates more poorly than those at mid- to low-latitudes. For example, comparisons of model simulations to observed late Quaternary spruce distributions in Alaska indicate that for certain times the model overestimates past summer temperatures and precipitation for this region, although for other areas (*e.g.*, eastern North America) the model does fairly well (Bartlein *et al.* 1998).

Comparison of long-term (20,000 and 120,000 year) records from different parts of the Arctic reveals variability in the response of different regions to climate forcing. The spatial extent, magnitude, and even sign of changes depend on a hierarchy of controls from global to subregional. For example, in some arctic regions early-Holocene insolation forcing was opposed by residual ice sheet presence, whereas in others it was not, leading to large variations in the spatial expression of response to the early-Holocene insolation maximum. On a smaller scale, variations in the long-wave pattern and in the position of major pressure centers, which themselves respond to global forcing, strongly influence regional and subregional patterns of climate response (Bartlein *et al.* 1992, Mock and Bartlein 1995, Mock *et al.* N.d., Edwards *et al.* N.d.)

Stimulated by these and other recent research findings, PALE investigators expect to concentrate next on the following problems:

- ⌘ Determining the significance of prominent 20th-century warming and coincident environmental changes in the context of changes that have occurred through the Holocene.
- ⌘ Refining estimates of how much arctic feedbacks (*e.g.*, snow and ice albedo, vegetation) amplify global and hemispheric climate change.
- ⌘ Describing and understanding the regional heterogeneity of vegetation and surface processes to environmental and climate feedback.
- ⌘ Documenting oceanic and near-shore records of past changes in sea level, sea-ice extent, and the paleogeography of water masses and ice sheets.

These investigations will clearly involve collaborations among PALE researchers and other ARCSS investigators (*e.g.*, LAII, OAI, GISP2) and the circumpolar research community (CAPE).

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Ocean-Atmosphere-Ice Interactions (OAI)

The Arctic Ocean, with its adjacent seas, is an interactive system comprising water, ice, air, biota, dissolved and suspended chemicals, and sediments. The arctic marine environment directly affects global climate and responds sensitively to climate perturbations originating outside the Arctic. The Ocean-Atmosphere-Ice Interactions (OAI) component of ARCSS investigates the arctic marine system in the context of global change. The first phase of OAI was influenced by the recognition that basic observations of this system have been sparse. First-order features of the arctic marine environment had not been described adequately, primarily because of logistical and political hurdles. Basic knowledge of seasonal, regional, and interannual variability was lacking, and coupling mechanisms thought to be crucial in scenarios of future changes remained highly speculative (*Arctic System Science: Ocean-Atmosphere-Ice Interactions* 1990, *Arctic System Science: OAI Initial Science Plan* 1992). Both large, multi-investigator programs and individual science projects with a systems approach are filling the gaps in our understanding of six major areas:

- ⌘ circulation in the Arctic,
- ⌘ surface energy budget, atmospheric radiation, and clouds,
 - ⌘ hydrological cycle of the Arctic Ocean,
 - ⌘ productivity and biogeochemical cycling,
 - ⌘ paleoceanography of the Arctic, and
 - ⌘ coupled model studies.

Approximately 80 principal investigators have been funded through OAI. Four collaborative projects have been fully or partially implemented:

- ⌘ the Northeast Water (NEW) Polynya study (1991–1994),
- ⌘ the Western Arctic Mooring (WAM) Program (1992–1995),
- ⌘ the joint U.S./Canada Arctic Ocean Section (AOS) study (1994–1996), and
- ⌘ the Surface Heat Budget of the Arctic Ocean (SHEBA) project (1995–2002).

The Northeast Water (NEW) Polynya project examined carbon fluxes on the continental shelf off Northeast Greenland to understand controls and feedbacks across major marine interfaces. Investigators took both an ecosystem and physicochemical approach to assessing carbon pathways in water masses and sediments. Results suggest a self-contained ecosystem in some years, with fixed carbon recycled or stored locally, and a

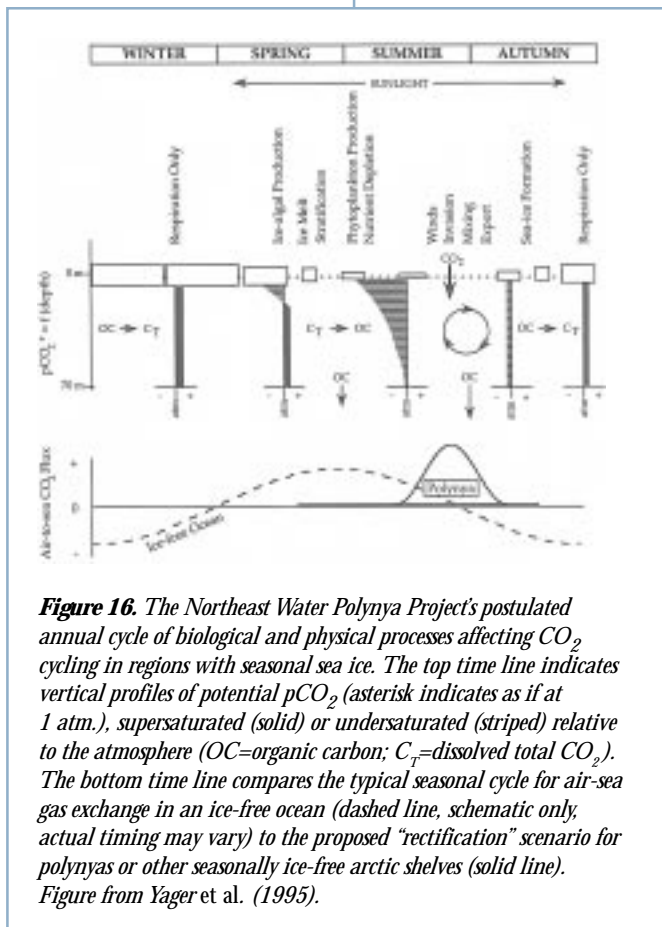


Figure 16. The Northeast Water Polynya Project's postulated annual cycle of biological and physical processes affecting CO_2 cycling in regions with seasonal sea ice. The top time line indicates vertical profiles of potential pCO_2^* (asterisk indicates as if at 1 atm.), supersaturated (solid) or undersaturated (striped) relative to the atmosphere (OC =organic carbon; C_T =dissolved total CO_2). The bottom time line compares the typical seasonal cycle for air-sea gas exchange in an ice-free ocean (dashed line, schematic only, actual timing may vary) to the proposed "rectification" scenario for polynyas or other seasonally ice-free arctic shelves (solid line). Figure from Yager et al. (1995).

potential off-shelf export in others. The results also support a seasonal rectification hypothesis, whereby the unique coupling of physical and biological processes in the region establishes this and possibly other continental shelves as a sink in the present-day global carbon budget (Figure 16; Yager *et al.* 1995).

The Western Arctic Mooring (WAM) Program quantified variability of Pacific inflow to the Arctic Ocean. The mean flux through the Bering Strait during 1990–1994 was 0.83 Sverdrup (Sv; one million cubic meters of water per second); the transport of 1.14 Sv during the first nine months of 1994 was likely the largest in the last 50 years. Large interannual salinity variations suggest a correspondingly variable density input to the Arctic Ocean halocline. The annual cycle of salinity in the Bering Strait indicates regional ice formation of 5 cm per day distributed relatively uniformly over the Chukchi Sea shelf. Part of the hypersaline water descends through Barrow Canyon without significant entrainment, while another part propagates across the outer shelf in bottom-confined anticyclonic eddies (Weingartner *et al.* 1998). The interannual variability in these various processes leads to strikingly different year-to-year manifestations of winter shelf-water properties and fluxes both onto and off the shelf. The transport of biogeochemical products on and off the shelf is likely to vary similarly.

The 1994 Arctic Ocean Section (AOS), the first major scientific crossing of the Arctic Ocean, sought to clarify the Arctic's role in global change (Tucker and Cate 1996). The 70 scientists aboard performed 49 constituent projects covering ocean circulation, the carbon cycle, past climates, contaminants, the ice cover, and atmospheric chemistry and physics. The results illuminate:

- ⌘ ocean warming and water mass displacements (Figure 17),
- ⌘ ocean ventilation,
- ⌘ freshwater cycling,
- ⌘ the role of sea ice in material transport,
- ⌘ primary production,
- ⌘ the microbial loop,
- ⌘ sinking of particulate organic carbon,
- ⌘ the impact of radionuclides, persistent organics, and metals on the marine ecosystem,
- ⌘ the radiative properties of the ice cover,
- ⌘ atmospheric radiation,
- ⌘ marine contributions to atmospheric chemistry, and
- ⌘ the marine sedimentation record, including crustal sources.

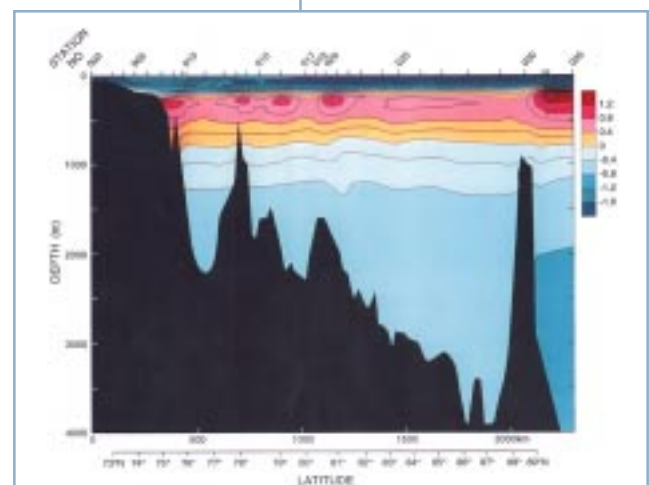


Figure 17. Work during the 1994 Arctic Ocean Section resulted in this potential temperature section from the Chukchi shelf (left) to the Eurasian flank of the Lomonosov Ridge (right). Note the warm cores at 200–400 m above each primary bathymetric feature. The multiple warm cores near the Chukchi boundary are mostly the same features seen winding along the topography as the ships worked their way into the interior of the Arctic Ocean. Figure from Aagaard *et al.* (1996).

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The ongoing Surface Heat Budget of the Arctic Ocean (SHEBA) study is designed to improve predictions of arctic climate by investigating the physical processes that determine the surface energy budget, sea-ice mass balance, and surface radiative properties in the Arctic Ocean (Moritz *et al.* 1993, Moritz and Perovich 1996). These processes are fundamental to the ice-albedo feedback mechanism that exerts strong influence on climate in the Arctic and, therefore, to simulations of past, present, and future climate in the region. The SHEBA program is composed of three phases:

- ⌘ Phase I—modeling studies and analysis of existing data sets (1995–97);
- ⌘ Phase II—a multi-season field experiment (Figure 18) to acquire critical observations with which to develop, test, and integrate improved climate models and remote sensing analyses of arctic pack ice zones (1997–99); and

- ⌘ Phase III—analysis and modeling to improve climate models, (*e.g.*, general circulation models; 2000–03).

Results from individual projects within OAI include:

- ⌘ Modeling studies of the thermodynamic interactions between the atmosphere and sea ice suggest that ice thickness in the central Arctic may undergo large (*ca.* 1 m) fluctuations on time scales of 1–15 years, in response to randomly varying poleward atmospheric heat flux (Bitz *et al.* 1996).
- ⌘ Limited seasonal studies indicate that rates of sediment denitrification in the Arctic are similar to the global average; since the Arctic contains 25% of the world's ocean shelves, denitrification in arctic shelf/slope sediments may constitute a major carbon loss in global carbon cycling (Devol *et al.* 1997).
- ⌘ A Lagrangian modeling effort of the Bering/Chukchi Sea ecosystem indicates a spring-summer extraction of nitrate from the water column and of CO₂ from the atmosphere, followed by fall-winter storage of ammonium and dissolved organic carbon near the shelf break of the Canadian Basin (Walsh *et al.* 1997).

A science plan has been published for the Western Arctic Shelf-Basin Interactions (SBI) initiative (Grebmeier and Whitley 1996,



Figure 18. A sketch, made during the planning phase, of elements of the SHEBA research camp on the pack ice. The camp, which headquarters about 25 people at a time, has been deployed in the pack ice of the eastern Beaufort Sea; changes in ice conditions and leads regularly affect the actual layout. (1) Satellite for monitoring atmospheric structure and surface parameters; (2) research aircraft for surveys of atmospheric and surface parameters; (3) rawinsonde; (4) instrumentation to measure the spectral distribution of downwelling radiation; (5) all-sky camera, ceilometer, and other instrumentation to measure cloud properties; (6) meteorological tower; (7) hydrohole and winch for deployment/recovery of suspended oceanographic instruments and AUVs; (8) stakes representing the measurement of the ice and snow mass balance, and temperature and radiation in the ice interior; (9) radiometers; (10) communications antenna; (11) mess hall; (12) generator shed; (13) living quarters; (14) laboratory; (15) submarine for surveying the ice thickness distribution. Figure provided by Norbert Untersteiner.

Grebmeier *et al.* 1998), which will investigate shelf, shelf break, and slope regions in the Arctic where important biogeochemical and physical processes undergo significant changes and modification that can be directly affected by global change (*e.g.*, ice-cover extent, freshwater input, seawater temperature variance). Among SBI objectives are improved predictions of the effects of global climate change on continental shelf biological productivity, shelf-basin interactions, basin-global circulation, biogeochemical cycling, and sea ice. SBI will include examinations of past and present environmental changes as steps in the development of models capable of predicting possible future responses to global change, including responses in Arctic Ocean circulation that could affect world fisheries. SBI will focus initially on the Chukchi and Beaufort seas region, partly because people in the region are concerned about the effects of environmental changes on traditional marine food resources. The SBI study region may later extend to include parts of the Russian Arctic, perhaps the East Siberian Sea.

Several other multi-investigator OAI initiatives are in various stages of development (Codispoti *et al.* 1997). They include:

- ⌘ the Study of Arctic Change, an initiative recognizing that the Arctic is in the midst of a significant physical change involving both the atmosphere and ocean. The results of several recent expeditions indicate that influence of Atlantic Water is rapidly becoming more widespread and intense than previously observed. The Study of Arctic Change will include regular measurements of atmosphere, ocean, ice, and some terrestrial parameters for at least the next decade, examination of historical records for evidence of such changes in the past, and a modeling effort to try to understand the causes of these changes.
- ⌘ a project to study the outflow of freshwater from the Canadian Archipelago and its relationship to North Atlantic Deep Water formation, and
- ⌘ a project to study the physical and biogeochemical oceanography of the Canada Basin, including its sensitivity to environmental forcing.

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New technology and automated data collection were critical to several LAII projects. The magnaprobe—an automated snow depth recorder developed by Matthew Sturm and Jon Holmgren—enabled investigation of the relationship between snow depth and tundra vegetation to rely on a database of 10,000 separate snow depths along transects from Alaska's Brooks Range to the coast. Below, Max König measures snow depth near the Toolik River with the magnaprobe. Photo by Glen Liston.



Land-Atmosphere-Ice Interactions (LAII)

The overall goal of LAII is to enhance our understanding of:

- ⌘ land-atmosphere-ice interactions in the arctic system,
- ⌘ the role that these processes play in the whole Earth system, and
- ⌘ the effect that global change may have on the Arctic.

The scientific questions of LAII are organized under four main themes:

- ① detection and analysis of global change,
- ② circumpolar extrapolation of climate feedbacks from arctic terrestrial ecosystems,
- ③ past and future changes within the arctic system, and
- ④ sustainability of the arctic system under global change.

LAII research is critical to understanding the arctic system because of:

- ⌘ large feedbacks to global climate due to seasonal and long-term changes in albedo and land-atmosphere energy exchange;
- ⌘ large frozen carbon reservoirs that can be a source of trace gases under warmer conditions;
- ⌘ inputs of freshwater, carbon, and nutrients to the ocean, which strongly influence oceanic productivity and circulation; and
- ⌘ large changes in human interactions with ecosystems, due to climatic impacts on ecosystem processes, permafrost integrity, and the global economy.

LAII's science plans have been outlined and updated in *Arctic System Science: Land/Atmosphere/Ice Interactions: A Plan for Action* (1991, 1997). Since its inception in 1991, 25 research projects have been funded by LAII. Half are integrated into a study of trace-gas fluxes in northern Alaska which has shown that tundra may be a source or a sink for CO₂ in summer, but is a net source in winter (Oechel *et al.* In press), while measurable CH₄ flux occurs only in summer (Whalen and Reeburgh 1992). The dominant environmental controls over fluxes of water, energy, and trace gases change completely from summer to winter. Winter variation in energy budgets is determined by radiation inputs; summer energy budgets are governed by evapotranspiration (Eugster *et al.* 1997), which depends on vegetation type and governs runoff to rivers. Moisture has opposing effects on the two major trace gases: CH₄ flux declines with soil drying, while CO₂ flux initially increases. These offsetting effects buffer the overall influence of the Arctic on climate forcing. The importance of terrestrial ecosystems in climate change scenarios depends on climatic, vegetation, and permafrost

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effects on soil moisture. Moisture directly regulates trace-gas fluxes and indirectly determines vegetation effects on surface energy exchange (Oechel *et al.* 1993).

Representations of the land surface in climate models, which have been developed in the context of global models and tropical, mid-latitude, and alpine regimes, are inadequate for simulations of the arctic climate system and may be related to the deficiencies observed in GCM simulations of the Arctic. These deficiencies lie in both the treatment of the soil hydrology, including permafrost, and the specification of high-latitude vegetation. Work is underway to rectify these problems in a way that is compatible with general circulation model development (Lynch *et al.* 1995).

Another group of projects is integrated into the International Tundra Experiment (ITEX), an international collaboration with strong U.S. involvement. By passively warming the tundra using small greenhouses at 26 circumpolar arctic and temperate alpine sites in 11 countries, ITEX seeks to understand the capacity of tundra plant communities to adapt to environmental changes; all ITEX projects monitor climate as well as phenology, growth, and reproduction in selected tundra plant species (Henry and Molau 1997). This basic experiment has shown that short-term responses of vegetation to manipulation may not parallel long-term responses because of major ecosystem feedbacks that compensate for or amplify initial responses (Chapin *et al.* 1995). The U.S. LAI contribution to ITEX extends the basic warming experiment to include a variety of related investigations (*e.g.*, effects of changes in snowpack, role of nutrient dynamics and population genetic mechanisms). Genetic studies show significant differences among plants in response to environmental factors associated with climate change. Many arctic ecosystems are more responsive to nutrients than to temperature, suggesting that some of the temperature effects on vegetation operate indirectly through controls on nutrient cycling (Chapin *et al.* 1995).

Other LAI studies address the interaction between human communities and the response of biotic systems to change. For example, social and economic factors strongly influence subsistence harvests of black brant in the Yukon-Kuskokwim Delta (Sedinger 1996). Grazing by black brant, in turn, determines the morphology of a key forage species (*Carex subspathacea*) and its impact on ecosystem processes (Person *et al.* 1998). Over-harvest of geese can lead to prolonged population depression, eventually reducing harvests, because decreased grazing reduces forage available to goslings in the future. In northeastern Alaska, both climate and development have important impacts on the energetics and calving success of the Porcupine Caribou Herd. Changes in the availability of caribou to northern communities for subsistence harvest can interact with changes in wage employment to affect the sustainability of village lifestyles in the region.

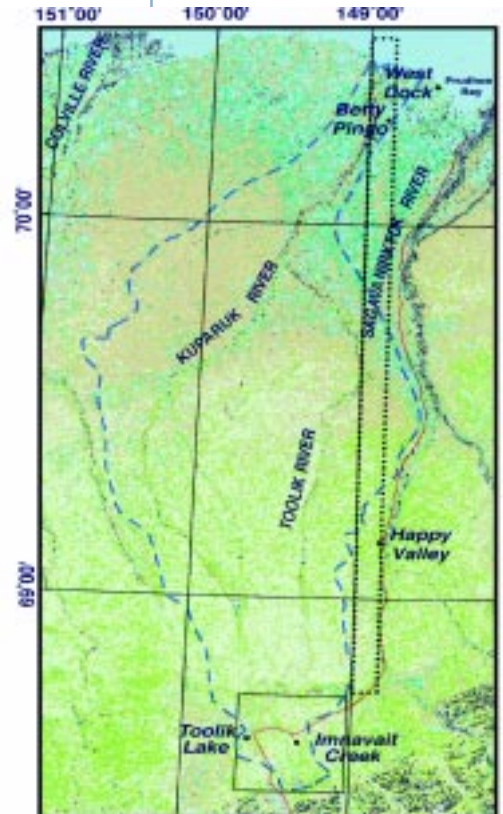


Figure 19. Results from the LAI Flux Study include the description of a previously unrecognized tundra vegetation, moist non-acidic tundra (shown in tan). Compared to moist acidic tundra (shown in yellow), previously thought to be the primary vegetation type on most moderately drained surfaces of the Alaskan North Slope, moist non-acidic tundra has fewer shrubs, more erect dead sedges, and more bare soil. Moist non-acidic tundra's ecosystem properties are relevant to energy, trace-gas, and water fluxes; recognizing the differences between these two tundra types is important in several arctic and global change issues. Figure from Muller et al. (In press).

ARCSS Program Research

A new LAII initiative now in the planning stage, Arctic Transitions in the Land-Atmosphere System (ATLAS), seeks to predict relationships among climate change and changes in vegetation and permafrost as well as carbon and energy exchanges with the atmosphere. LAII researchers hope to include in the ATLAS initiative a meteorology and hydrology component that takes into account differences in climate and soil moisture over increasing scales in time and space to predict changes in runoff and energy exchange. The ATLAS study region, which includes the North Slope and the Seward Peninsula, overlaps the OAIL-SBI study region. As in the case of SBI, ATLAS may later extend to the Russian Arctic, perhaps to Chukotka.

Integrative Studies

Synthesis, Integration, and Modeling Studies (SIMS)

The Synthesis, Integration, and Modeling Studies (SIMS) are designed to achieve a systems understanding of the arctic region. For this reason, SIMS projects are not a separate ARCSS component like OAIL, LAII, or Paleoenvironmental Studies (*Modeling the Arctic System* 1997). Projects that fit under the SIMS umbrella include those that:

- ⌘ consider the interaction of the Arctic with the global system,
- ⌘ span two or more of the ARCSS components,

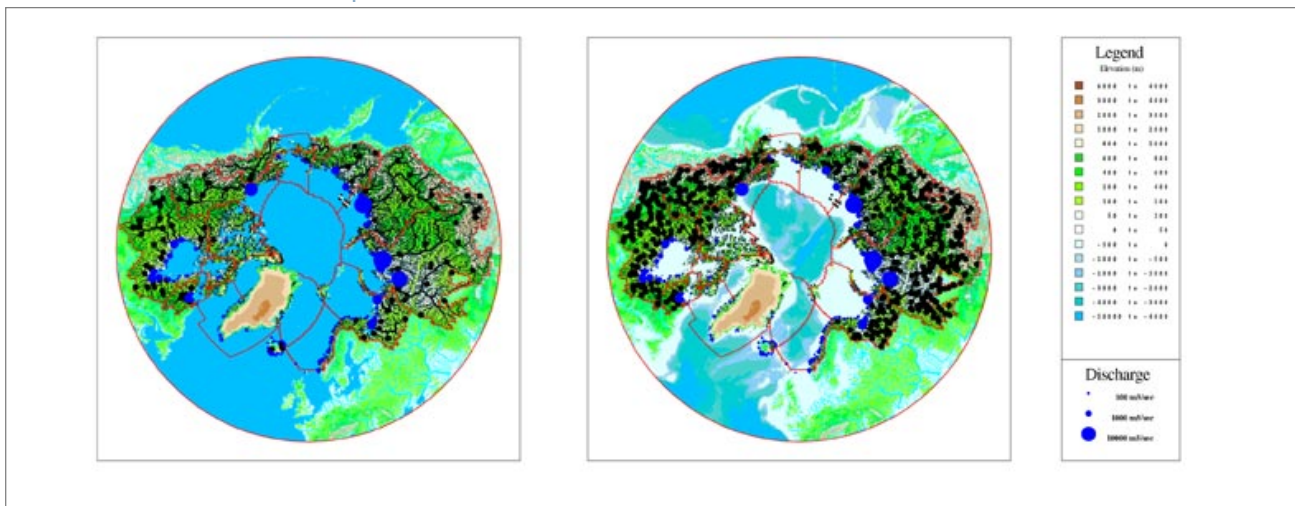


Figure 20. A summary of the Pan-Arctic Drainage project, which seeks to estimate contemporary water and constituent balances for the entire land area of the Pan-Arctic drainage system, including the drainage region of Hudson and James bays as well as the Yukon and Anadyr rivers entering the Bering Sea. The black dots represent river discharge gauges for drainage basins greater than 15,000 km². The left panel shows those gauges available at the beginning of the project, which originated from the UNESCO RivDis data set (Vörösmarty et al. 1996) and number approximately 90 gauges. The panel on the right shows the current set of gauges from large drainage basins, which include some 650 gauges. The total number of gauges collected so far of all sizes is over 7,700. Under the Global Hydrological Archive and Analysis System, new data have been collected from the United States Geological Survey, Environment Canada, and the State Hydrological Institute in St. Petersburg, Russia. Also included in the panels are delineations of seas within the Arctic Ocean and their drainage systems (red lines), which will allow estimates of regional freshwater fluxes to the Arctic Ocean. The blue circles represent current estimates of discharges to the Ocean for both gauged and ungauged basins based on model simulations. Circle size is a function of the estimated magnitude of discharge at each river mouth. Figure provided by Richard Lammers, Global Hydrology Laboratory, Complex Systems Research Center, University of New Hampshire, in collaboration with Bruce Peterson, Marine Biological Laboratory.

- ☼ synthesize ARCSS data with results from other large global change programs, and/or
- ☼ bring together (*e.g.*, model) elements of different disciplines.

Modeling is an important aspect of this initiative, integrating information about a system from different disciplines at and across particular temporal and spatial scales. For example, a project that models contemporary soil, river, and estuarine hydrology and their impacts on the stability and structure of the Arctic Ocean circulation may integrate information from both LAII and OAI (see Figure 20). Other projects model various components of the arctic system, extending from one region to another, providing inputs from one component to another, or developing scaling algorithms. One SIMS project takes another approach, integrating data from several different sources (*e.g.*, ice cores, marine sediments) with contemporary and historical records (see Figure 21). In each case, these syntheses make valuable contributions to an ultimate goal of credible predictions.

ARCSS Program Research

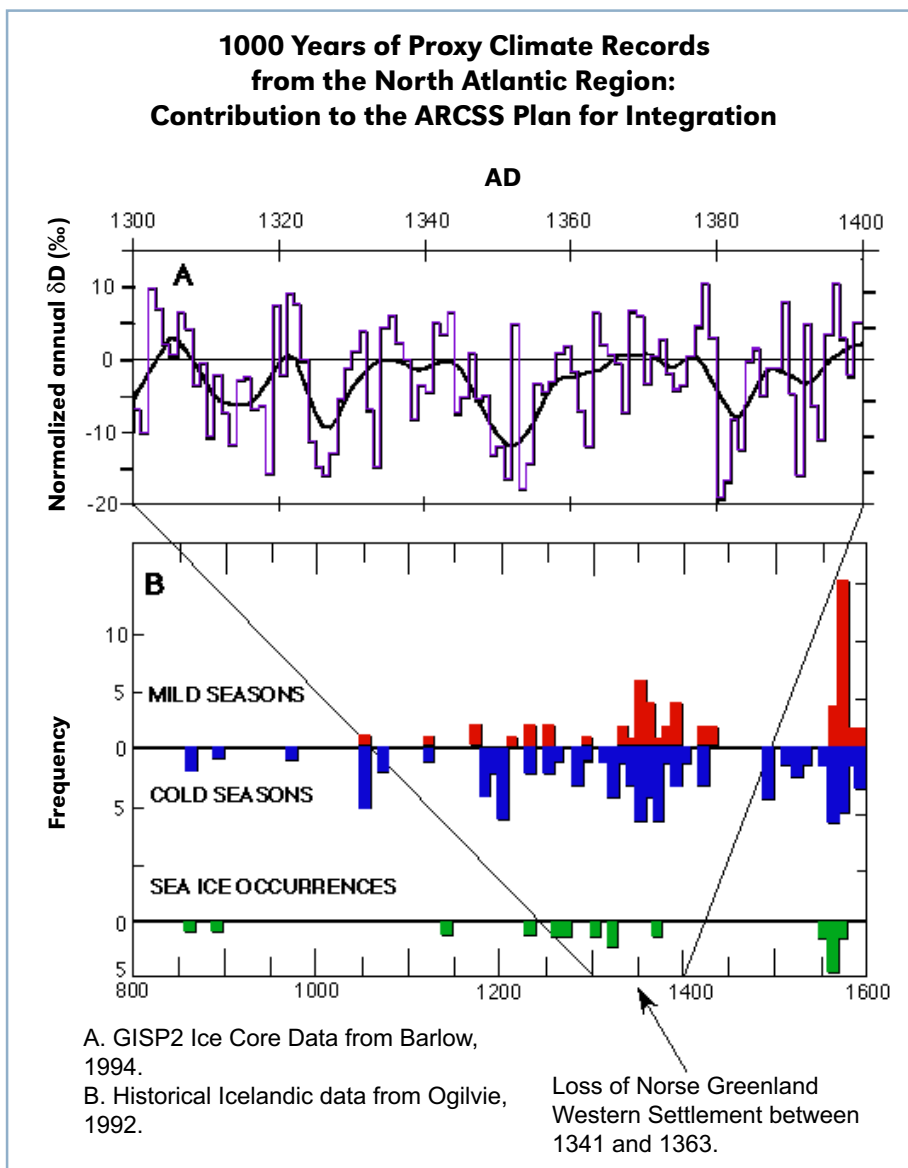


Figure 21. The loss of the Norse Western Settlement in Greenland around the mid-14th century AD has been investigated by an interdisciplinary team. High-resolution isotopic data from the GISP2 ice core (Diagram A) suggest a period of relatively lower temperatures (when normalised to a 700-year mean) ca. 1343–62. Seasonal isotopic data indicate that this temperature excursion was greater in the summer (Barlow et al. 1997). Historical records place the loss of the settlement sometime between ca. 1341 and 1363 (Ogilvie 1998). Diagram B shows historical temperature and sea-ice data for Iceland. The fourteenth-century evidence suggests that this may have been a time of great variability in this region of the North Atlantic. Exceptionally cold winters in Iceland are described for 1341, 1348, 1349, 1350, 1351, 1355, 1362, and 1365 (Ogilvie 1991). It should not be inferred, however, that changing climate was the sole culprit in the demise of the Norse Greenland Western settlement. Archaeological, paleo-ecological, and historical data suggest that the settlement had little cultural flexibility to aid its adaptation to adverse climatic conditions (Barlow et al. 1997).

ARCSS Program Research

New Initiatives

Human Dimensions of the Arctic System (HARC)

Because arctic residents are likely both to cause and be affected by major environmental changes in the region in the coming decades, and because these changes will spill over to affect people in mid-latitudes, the ARCSS Program recognizes the importance of research on the human dimensions of global change. Throughout history, human activity in the Arctic has caused significant environmental, economic, social, and cultural change. Humans are also catalysts of change on global as well as regional scales. The environment dominates many aspects of daily life in the Arctic and environmental changes are likely to have immediate, important consequences for arctic peoples. Over the course of the first eight years of the ARCSS Program, investigations of physical and biological components of the arctic system have matured sufficiently that scientists can now:

- ⌘ incorporate information about human interactions with the environment into their research,
- ⌘ assess the implications of global changes for residents of the Arctic,
- ⌘ assess the implications of arctic system changes for residents of other regions (*e.g.*, those who depend upon North Atlantic and Bering Sea fisheries).

In 1993, arctic scientists and indigenous knowledge experts began planning a research initiative to fully integrate human-dimensions research into the ARCSS Program. *People and the Arctic: A Prospectus for Research on the Human Dimensions of the Arctic System (HARC)* was published by ARCUS in 1997, and an NSF announcement of opportunity for the initiative is expected in 1998. The HARC initiative will integrate and synthesize research across programmatic, disciplinary, and geographic boundaries. A major concern of the HARC initiative is to assist arctic peoples to understand and

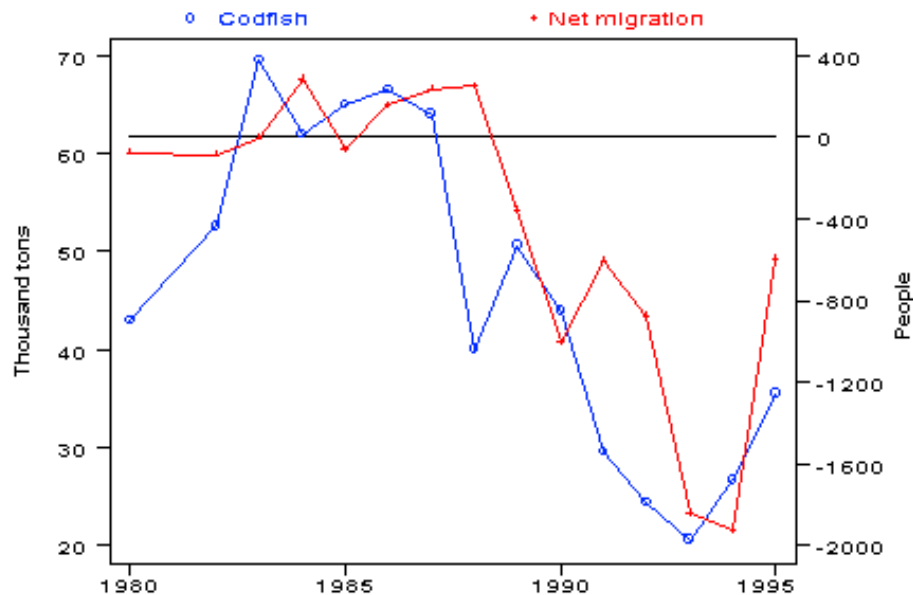


Figure 22. Faroe Islands cod landings fell during the late 1980s and human out-migration soon followed. The Islands' population declined 9% between 1989 and 1995. Figure from Hamilton (In press).

respond to effects of large-scale changes. In addition, just as the ARCSS Program as a whole examines effects of the arctic system on global climate, the HARC initiative recognizes the importance of exploring effects of past, present, and future changes in the arctic system on people living outside the Arctic. Results from HARC research will help policy makers assess and respond to impacts of climate change and other large-scale changes. Large-scale changes in the arctic system that affect humans and social systems include contamination of resources, habitat loss, elevated levels of ultraviolet radiation, competition for fish and wildlife, shifting cultural values, world-market effects on local economies, and increased resistance of diseases to treatment. Movement of persistent contaminants into arctic ecosystems, for example, is of concern because of probable negative effects on both the ecosystems themselves and the indigenous people who depend on the ecosystems' resources.

Human dimensions work has already begun in other ARCSS components and will integrate with the new HARC initiative. For example, *Arctic System Science: Land/Atmosphere/Ice Interactions: A Plan for Action* (1997) places an increased emphasis on the human dimensions of global change. How will global change impacts on arctic ecosystems affect resource use by people living and working in and outside the Arctic? Potential effects of changes in resource availability range from changes in the ability of indigenous peoples to obtain food to changes in the price of oil. The human dimensions component of LAII significantly strengthens the policy relevance of studies of arctic feedback processes.

OAI's next large initiative, the Shelf-Basin Interactions (SBI) program, offers an excellent opportunity for integration with HARC researchers; SBI will have a regional focus in the Chukchi and Beaufort seas, in part because important regional concerns, such as marine resource use issues (*e.g.*, hunting and food availability) are associated with these shelves. During the first phase of SBI, researchers will examine existing data collected by such agencies as the Minerals Management Service, Office of Naval Research, and U.S. Fish and Wildlife Service, as well as NSF and numerous international programs. SBI research initially will concentrate on outer shelf and slope interactions; near-shore ice dynamics, offshore development, and other issues of concern to northern residents could be developed as complementary topics.

Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE)

Another ARCSS initiative in the planning stage, the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE) will begin in the Eurasian Arctic, documenting changes in river discharge, permafrost dynamics, biodiversity, and continental ice sheets over the past 20,000 years as a means of improving our understanding of the arctic land-shelf system. Like SBI, RAISE research will have an ecosystem focus. RAISE will primarily consider land-shelf interactions while SBI will largely emphasize shelf-basin interactions. The ATLAS investigations of climate, soil moisture, and vegetation interactions complement the larger scale RAISE focus on river discharge (Forman and Johnson N.d.).

ARCSS Program Research

International Collaboration

ARCSS Program research, which investigates the role and response of the arctic system in global environmental change, complements other national and international programs. The ARCSS Program is pursuing collaborations to improve predictions of future change in the Arctic and other areas of the world. Investigators in the eight nations that border the Arctic Ocean—Canada, Finland, Greenland/Denmark, Iceland, Norway, Russia, Sweden, and the U.S.—recognize that international collaboration is essential for a real understanding of the region, including, from the U.S. perspective, the success of ARCSS Program research. All ARCSS Program components contribute to international initiatives, compelling an integrated approach to research (see preceding sections and box on facing page). The inclusion of arctic components within international global change programs facilitates international cooperation and provides opportunities for joint and enhanced research in the circumpolar Arctic. The rapidly developing international collaborations of the ARCSS Program will:

- ⌘ build new international research collaborations and expand existing ones,
- ⌘ enhance availability and exchange of data, including historical data,
- ⌘ share research platforms,
- ⌘ coordinate field work to obtain maximum spatial and temporal coverage,
- ⌘ cooperate in developing new technologies,
- ⌘ recognize that the Arctic, unlike the Antarctic, is inhabited by humans, and
- ⌘ protect the rights of these northern peoples.

Emerging and ongoing programs offer opportunities for continued and expanded international cooperation, including the:

- ⌘ coordination of programs planned to monitor arctic change, such as the European Variability and Exchanges in the Nordic Seas (VEINS) Program, which investigates major fluxes through northern seas; the Canadian throughflow experiment, recording similar parameters in Canadian waters; the new U.K. Arctic Ice and Environmental Variability (ARCICE) Program, which seeks to document and predict variations in the arctic cryosphere relevant to climate and sea-level change in northwest Europe; and the emerging U.S. Arctic Change initiative (see page 19);
- ⌘ close interaction of U.S. and Russian scientists in the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE) initiative, with increased focus on, and access to, the Russian Arctic (see page 25); and
- ⌘ the new International Arctic Research Center (IARC) as a nucleus for U.S.-Japan collaborations with international climate change

programs through the Japanese Frontier Program. IARC will serve as a headquarters where investigators can share information about a variety of natural phenomena that occur in the Arctic, particularly relating to global change. A program of IARC affiliates is being designed to facilitate participation by arctic researchers from the U.S., Japan, and the international research community. Research initiatives identified in the IARC science plan include arctic climate, arctic hydrological cycle, global warming, atmospheric compounds, arctic ecosystems, tectonic hazards in the arctic region, socioeconomic impacts of global change in the Arctic, and middle and upper atmosphere.

ARCSS Program Contributions to Joint International Programs

Collaborative international programs have contributed substantially to our understanding of the Arctic. Examples of projects supported by the ARCSS Program that have made significant contributions to broader international efforts include:

- ⌘ The Arctic Climate System Study (ACSYS) of the World Climate Research Programme (WCRP) complements and extends the polar components of various national and international climatic projects. The 1994 joint Canada/U.S. Arctic Ocean section was a concrete step towards realizing ACSYS goals of providing an adequate scientific basis for representation of the Arctic in coupled global models, developing plans for effective climate monitoring in the Arctic, and determining the role of the Arctic in the sensitivity and variability of global climate.
- ⌘ The Past Global Changes (PAGES) project of the International Geosphere-Biosphere Programme (IGBP) and the supporting Earth System History (ESH) Program at NSF—a component of the USGCRP—seek to understand the evolution of past environmental change in the Arctic and how past arctic changes relate to changes elsewhere in the global system. Arctic initiatives within PAGES include GRIP, GISP2, and the new CAPE (Circum-Arctic PaleoEnvironments) initiative, all established to obtain and interpret high-quality paleoclimatic records and provide the data needed to assess and validate predictive climate models. PAGES has developed a global paleoenvironmental database, enabling widespread data sharing and collaboration.
- ⌘ The Surface Heat Budget of the Arctic Ocean (SHEBA) Program cooperates closely with the International Arctic Buoy Program (IABP), a joint effort sponsored by the World Meteorological Organization, UNESCO, and the Data Buoy Cooperation Panel. Data from satellite-tracked buoys in the Arctic have characterized the global circulation patterns of arctic sea ice and recently shown that sea-ice extent decreased more than 5% over the period 1987–1995.
- ⌘ The International Tundra Experiment (ITEX) is a coordinated, circumarctic-alpine experiment on the responses of selected plant species to a 2-5°C summer warming. ITEX researchers in 11 countries, including scientists supported through LAII, follow a published set of protocols to enable meaningful synthetic analysis on combined data sets. Initial analysis indicates patterns that may significantly alter existing understanding of plant responses to warming. For example, compared to low-arctic or alpine sites, high-arctic sites show little response to warming, perhaps due to low nutrient availability.

Priorities for the Future

During the early years of the ARCSS Program, research priorities were driven by the premise that the Arctic might have a major role in, and be greatly affected by, global change. The research carried out over the last eight years has largely supported this perspective. For example, evidence gathered under the ARCSS Program confirms that the Arctic Ocean has a disproportionately large influence on the dynamics of ocean circulation and that the effects of this influence can vary on quite short time scales. As the ARCSS Program's initial projects answer first-order questions about mechanisms, feedbacks, and processes, the data guide the development of a wider perspective—a comprehensive systems approach to understanding accumulating results, identifying relevant gaps, and proposing new efforts.

Research Questions

In planning and implementing new research, the ARCSS Program will strive to address five broad questions that have developed from the more programmatic—and somewhat disciplinary—orientation of questions posed in the previous science plan, *Arctic System Science: A Plan for Integration* (1993). Because basic information about and understanding of the arctic system have increased, these five questions indicate new directions along which programs and individual research projects can connect to advance deeper explanations and more reliable predictions. The five questions and associated goals and topics of interest are:

① ***How will the Arctic climate change over the next 50 to 100 years?***

Virtually all aspects of the arctic system are affected by climatic change, on varying temporal and spatial scales. For this reason, accurate predictions of arctic climate are a foundation of Arctic System Science. A primary goal of ARCSS research is to use integrated contemporary and paleoenvironmental observational, process, and modeling studies to assess future, near-term arctic climate change. These studies will seek to predict:

- ⌘ rates of future change,
- ⌘ changes in seasonality,
- ⌘ changes in variability,
- ⌘ spatial patterns at local, regional, and global scales,
- ⌘ magnitudes and nature of potential climatic feedbacks, and
- ⌘ unanticipated changes in the zonal status of arctic climates.

An integrated understanding of land, shelf, and ocean climate feedbacks is developing from the data generated by individual ARCSS components, which can be applied to common global and regional climate models; the resulting models will be tested with paleoclimate data.

② *How will human activities interact with future global change to affect the sustainability of natural ecosystems and human societies?*

Proposed global change scenarios indicate major impacts on arctic ecosystems that may have serious societal consequences. Programs of observation, experimentation, and modeling are needed to assess the validity of these predictions, to provide realistic predictions about the nature and rates of change likely to occur in biological and social systems given these scenarios, to propose policy responses to these changes, and to predict the effects of such policies (Walker and Steffen 1997). Key short-term objectives for programs to achieve these goals include:

- ⌘ designing programs of observations and experiments to test the validity of these predicted sensitivities;
- ⌘ developing process-based models that predict the future states of ecosystems and societies as a function of variables that are expected to change in the next 10 to 100 years;
- ⌘ performing sensitivity tests to identify combinations of variables that will have the greatest impact on critical ecosystem and societal processes; and
- ⌘ assessing costs and benefits of policy options that might mitigate undesirable effects.

Since most of the arctic regions' people live along the coast, land-sea climate interactions are critical to this question. Predicted sea-level increases will threaten coastal communities both in the Arctic and globally. Thawing permafrost will have widespread effects on arctic ecosystems and infrastructures. Other major questions identified in the HARC initiative include how climate change will interact with petroleum development (both offshore and onshore), hard-rock mining, long-range transport of contaminants, and increased use of the Arctic by lower latitude residents.

③ *How will changes in arctic biogeochemical cycles and feedbacks affect arctic and global systems?*

Changes in marine and terrestrial carbon and nitrogen cycles affect the structure and function of ecosystems and will, consequently, influence feedbacks from the Arctic to global cycles by altering fluxes of trace gases to the atmosphere and by altering the chemistry and buoyancy of Arctic Ocean waters entering the North Atlantic. Models of changes in marine and terrestrial biogeochemical cycles should be tested through comparison with paleoenvironmental time-series data that provide proxy measurements for ecosystem community structure, nitrogen-cycle activity, and sea-ice extent. A demonstrated ability to simulate past and current changes in biogeochemical cycles will increase confidence in predictions. An important goal of the ARCSS Program is to develop models that predict how changes in climate and human activities affect biogeochemical cycles that control

The Future of the ARCSS Program

the productivity and structure of arctic ecosystems. Major issues include the effects of:

- ⌘ warming on soil mineralization processes and plant growth;
- ⌘ changes in river runoff and nutrient export on coastal ecosystems;
- ⌘ altered sea-ice cover on shelf productivity; and
- ⌘ changes in the influx of Pacific water with its high nitrogen content on the Bering Sea ecosystem as well as the Arctic Ocean halocline.

Arctic marine environments, soils, and peatlands may be important sources and sinks of global CO₂ and CH₄. Processes that control the net release or uptake of these gases involve strong biotic feedbacks and respond sensitively to local changes in moisture and temperature. Further research is needed concerning the:

- ⌘ processes regulating marine and terrestrial carbon and nitrogen cycles (*e.g.*, the effect of warming in the Arctic on rates of CH₄ release from soils and on marine microbial regeneration patterns);
- ⌘ effects of increasing temperatures on arctic ecosystems, normally limited by short growing seasons, low temperatures, and low rates of nutrient cycling (*e.g.*, abundance and species composition of primary producers at the base of arctic food webs supporting migratory waterfowl, caribou, marine mammals, and indigenous societies);
- ⌘ effects of thawing permafrost, which increases availability of soil nutrients to plants, improves drainage, and increases flux of nitrogen and phosphorus from land to streams, lakes, and oceans;
- ⌘ effects of changes in sea ice, nutrient availability, and water density on arctic marine ecosystems and associated biochemical cycling of essential nutrients.

Through the combined understandings of arctic biogeochemical processes developed through ARCSS, researchers should be able to develop the first integrated models of regional changes in arctic marine and terrestrial ecosystems, including changes in species of direct importance to people living in the Arctic. This improved biogeochemical knowledge will also sharpen global climate models' predictive ability by including projections from integrated models of changes in greenhouse gas emissions from the Arctic.

④ *How will changes in arctic hydrologic cycles and feedbacks affect arctic and global systems?*

Arctic hydrologic change exerts important influences on systems both within and outside the Arctic. Observations and models suggest that the largest potential impact of this change on the global system, including human societies, is through impacts on the global ocean thermohaline system. Paleoenvironmental data and contemporary observations show clearly that the strength of the thermohaline system, which regulates global ocean

circulation, can vary significantly on time scales of years to centuries. Paleoclimatic data also indicate that this system can switch between significantly different modes in a matter of decades and, thus, abruptly affect such phenomena as the northward transport of heat by surface ocean currents.

A major goal of the ARCSS Program is to develop a well-validated ability to predict arctic impacts on global thermohaline circulation, which requires an improved, detailed understanding of the arctic hydrologic cycle, including:

- ⌘ describing the role of sea ice in the regulation of runoff over the arctic shelves;
- ⌘ delineating how buoyancy fluxes are distributed in space and time over the convective regions of the North Atlantic;
- ⌘ evaluating how well arctic influences on thermohaline circulation can be simulated, particularly in situations involving significant change that cannot be evaluated using instrumental data alone (paleoclimatic/oceanographic studies);
- ⌘ developing climate models to simulate precipitation, evaporation, cloud cover, and their impacts in the Arctic, where differences in patterns of radiation, the presence of permafrost and sea ice, and the composition of vegetation render models based on other regions inadequate;
- ⌘ assessing, through hydrological studies, the likelihood that toxic contaminants (*e.g.*, radionuclides, persistent organics, heavy metals) in the Arctic might be remobilized and where such contaminants might be redistributed; and
- ⌘ refining hydrologic studies to assess accurately terrestrial and marine ecosystem change.

Collaborations among ATLAS, RAISE, SBI, and PALE researchers will enhance research on these complex systems. Data from ATLAS promises to improve understanding of small-scale processes that produce the large-scale changes in river discharge that will be a key focus of RAISE researchers. RAISE and SBI researchers may be able to use this understanding to predict changes in freshwater inputs to the shelf-basin system. In combination with results from other OAI initiatives, these data could provide the basis for predicting the consequences of changes to North Atlantic ocean circulation and thereby to environmental changes of substantial importance to people—changes in fisheries, for example.

⑤ *Are predicted changes in the arctic system detectable?*

ARCSS assessments of arctic system change will be based on carefully developed and tested models. Variability in past and current ecosystems is used to predict possible global change effects. Important exercises include:

- ⌘ regular comparisons of predictions from models with reconstructions from modern and paleoenvironmental time series to provide evidence that predicted changes are actually taking place, as well as to test and refine the predictive process;

The Future of the ARCSS Program

- ⌘ identification and monitoring of arctic system elements that are particularly sensitive to environmental change, including physical (*e.g.*, climatic, oceanographic, glaciological) and biological (*e.g.*, marine and terrestrial wildlife, human systems) constituents of both terrestrial and marine systems.

Separating natural climate signals from human-induced climate change remains a somewhat inscrutable problem. Paleoenvironmental researchers will contribute an invaluable context of past climate change. LAII and OAI researchers are measuring current indicators of climate change. Research under HARC will incorporate human dimensions into work on the arctic system. Collaborations with other international efforts should allow development of a circumarctic view of past and current climate change and related changes in arctic ecosystems. Such a comprehensive view will continue to require a systematic amalgamation of current and past marine and terrestrial measurements, as with RAISE.

Integrative Strategies

As the ARCSS Program matures, generating important basic data from its component projects, an assessment of future research questions and needs is timely. ARCSS investigators now have adequate experience to recommend effective strategies and mechanisms for efficiently accomplishing future work and for thoroughly integrating individual projects into a wider arctic and, eventually, global perspective. The organization of ARCSS science planning under programmatic components has had the advantage of building on traditionally strong disciplinary affiliations. The important research questions that can be addressed within each component of ARCSS are virtually endless. Increasingly, however, the demanding arctic system questions cut across disciplinary and programmatic boundaries: To what extent will changes in ocean circulation bring contaminants to marine mammals? How will changes in sea-ice extent alter prospects for development in the Arctic? Will a combination of natural and human-induced climate changes produce major changes in North Atlantic fisheries?

Because most of these important questions call for predictions of the future, the scientific community never will be able to answer them conclusively. Through diligent science, strategic collaboration, and an accumulating understanding of the arctic system, however, the ARCSS Program can investigate these questions and offer an empirical basis for informed discussion. For the ARCSS Program to achieve a predictive understanding of arctic system dynamics, particular attention must be given to integrating elements of the research. The integrating approaches described below are common to all programs and projects within ARCSS, and data from individual projects will contribute fundamentally to these broader perspectives.

① *Integrating instrumental and paleoenvironmental data*

Paleoenvironmental research plays a crucial role in the integration of future research activities. Further efforts will build upon the successes of GISP2 and PALE, using appropriate sources of paleoenvironmental information and modern observations to:

- ⌘ define the range of natural environmental variability over various temporal and spatial scales (observational studies),
- ⌘ understand the forcing and mechanisms behind the full range of variability (process studies),
- ⌘ identify previously unanticipated responses in arctic environmental systems,
- ⌘ test and improve predictive models iteratively, particularly with respect to altered forcing, and
- ⌘ detect environmental changes and attribute such changes to their respective or combined forcing mechanisms.

An important issue to be addressed in the integration of paleoenvironmental and contemporary data is that of incompatible data types, scale, and quality.

Whereas past ARCSS Program paleoenvironmental research has focused on the development and use of ice-core (GISP2) and sediment (PALE) records, expanded efforts should draw upon other proxy sources of information. This will be accomplished, in part, through closer programmatic interaction with the NSF Earth System History (ESH) Program and international coordination with the various arctic paleoenvironmental programs of the International Geosphere-Biosphere Programme (IGBP) Past Global Changes (PAGES) Core Project.

② *Scaling between local, regional, and global processes*

Many physical processes of the Arctic, whether they are climatic, ecological, or biogeochemical, are influenced by mechanisms that operate across different spatial scales. For this reason, special attention must be given to understanding how processes can be scaled up from local scales to watersheds, regions, and, in many cases, to the scale of global climate models. Likewise, the capacity to scale down from global to local scales is critical for understanding environmentally driven impacts on human activities.

The issue of scaling applies to both observation- and model-based research efforts. In the case of observations, ARCSS research must promote an understanding of how detailed local-scale process studies can be scaled up to large regions, or how a particular paleoclimatic time series relates to a larger region. Special emphasis must be placed on developing the hierarchy of models needed to simulate realistic environmental change in the Arctic. The ARCSS Program will have to promote careful integration of observations, process studies, and models to achieve its goals.

The Future of the ARCSS Program

③ *Model development*

While many groups worldwide are working to develop climate models, little attention has been paid to the ability of state-of-the-art models to simulate climate in the Arctic. Arctic system research depends on the performance of such models. To place the arctic system in a global context, global climate models are needed that provide accurate regional climate outputs, either directly or coupled with regional models. Global climate models also must take into account arctic feedbacks to the global system. The ARCSS community is making progress in assessing the abilities of general circulation models and coupled general circulation models-regional models to predict arctic regional climate and to handle arctic feedback; this knowledge must be applied in a coordinated approach to the enhancement and application of climate models throughout the ARCSS Program.

④ *Development of an effective framework for evaluating models*

Because future climate forcing is likely to be unprecedented, numerical (process) modeling is essential for developing reliable predictions of change. The ARCSS Program must ensure that data sets appropriate for rigorous model evaluation are developed. In most cases, data from instrumentation, satellites, and monitoring sites will provide an excellent way to evaluate how well various models simulate contemporary “equilibrium” conditions; these data, however, will be too short range to test the capacity of models to simulate change. Paleoenvironmental models provide the long-range framework necessary to assess contemporary data and to predict and detect change. For this reason, a framework for rigorous evaluation of long-range paleoenvironmental models is necessary. This environmental change framework must incorporate data from all available sources and must link with the international focus on paleoenvironmental model evaluation, such as that associated with the International Geosphere-Biosphere Program/World Climate Research Program’s Paleoclimate Modeling Intercomparison Project (PMIP).

Coordination and Integration

The planning and management structures of the ARCSS Program, based in the contributions of the scientific community, generally have worked well over the past eight years. Specific recommendations for community coordination and integration infrastructure and logistics support needed to facilitate ARCSS research are included below.

Logistics Support

Logistics in the Arctic often have been opportunistic, utilizing the resources of other nations. Despite limited logistical support, U.S. scientists have carried out a tremendous amount of high-quality arctic research, much of it resulting from efforts of individual investigators or major programs based in a single geographic region or disciplinary inquiry. Research in the Arctic, including the cross-disciplinary, integrated research of the ARCSS Program, has entered a new era, however, recognizing that natural processes—marine, atmosphere, terrestrial, and social—interact across boundaries. Understanding global change requires study of the entire Arctic and its role within the global system. The logistics support needed to carry out detailed process studies year round and to collect spatially and temporally adequate data to understand system processes and to calibrate models is critical to the ability to predict global change accurately.

The arctic region presents major challenges, both technological and financial, to research logistics. The U.S. Arctic Research Commission (USARC) has recently made recommendations (Schlosser *et al.* 1997) relevant to ARCSS Program research logistics. The five general recommendations are:

- ⌘ Ensure access to the Arctic over the entire year.
- ⌘ Increase availability and use of remote and autonomous instruments.
- ⌘ Protect the health and safety of people conducting research in the Arctic.
- ⌘ Improve communication and collaboration between arctic peoples and the research community.
- ⌘ Seek interagency, international, and bilateral logistics arrangements to use efficiently all available resources and to reduce costs by avoiding duplication of efforts.

NSF already has taken several important steps to improve logistics support for arctic research. If implemented, the priority recommendations will substantially enhance the ability of ARCSS Program scientists to carry out research on the arctic system and global change.

Working with Arctic Residents

Arctic residents have concerns that can be addressed by the ARCSS Program; they also have concerns about the impacts of research itself. Communication and coordination between scientists and arctic communities will help ensure that the ARCSS Program is responsive to concerns. Researchers and residents can work cooperatively to ensure the success of the Program. Indigenous knowledge can be valuable to research on the arctic system, especially concerning human and environment interactions. Arctic residents may provide insights into methods and procedures that will improve a project and its chance of success.

The Program's components examine issues important to local governments, Native organizations, and the general population. Research permission should be obtained from appropriate local governments and efforts should be made to communicate findings back to the communities involved, including, if feasible, giving presentations at local schools and community centers in order to encourage a new generation of northern residents to participate in future research initiatives. All ARCSS researchers must follow NSF's protocols for the conduct of research, including *Principles for the Conduct of Research in the Arctic* (1990).

Community Planning and Science Management

ARCSS is a unique program within the National Science Foundation because:

- ⌘ it is defined geographically rather than by a scientific discipline, and
- ⌘ it supports mainly large, integrated, multidisciplinary research projects that are developed by the research community through workshops and science steering committees (SSCs).

The ARCSS Program is an NSF Global Change Program, and all of the projects supported by the Program address global change issues. While the ARCSS Program welcomes single-investigator projects with a global change focus, it will continue to encourage the arctic scientific community to develop interdisciplinary research projects that address problems requiring multiple disciplines and an emphasis on the entire arctic system. The system science approach requires an extraordinary need for ongoing community planning, consensus, and cooperation among scientists from diverse disciplines. This cooperation extends beyond normal exchanges among individual investigators, institutions, and agency program managers. To guide successfully a suite of large, integrated research programs in this context, the programs must be coordinated from the initial planning stage, through implementation, data collection and dissemination, to the timely sharing of results with colleagues participating in the project.

The ARCSS organizational structure facilitates direct links between the NSF ARCSS Program Director and the research community, while encouraging a vital process of community participation and leadership. In particular, this structure maintains the peer review process that ensures

the scientific merit of proposals by individual principal investigators, while at the same time providing a mechanism to prioritize and coordinate research activities. The objectives of the ARCSS coordination infrastructure are:

- ⌘ to define and refine continually the overall concept, focus, and structure of the program;
- ⌘ to provide for periodic, independent review of the ARCSS Program's contributions to overall scientific progress and to global change research;
- ⌘ to facilitate communication, information exchange, and coordination of activities and resources among investigators;
- ⌘ to maintain scientific balance within a coherent interdisciplinary program;
- ⌘ to provide coordination and liaison functions with appropriate interagency and international groups;
- ⌘ to provide information, coordination, and planning of logistics in support of field programs;
- ⌘ to organize and administer program-wide data sets.

ARCSS Committee

The ARCSS Committee (AC) provides information to the NSF ARCSS Program Director on the development of the overall ARCSS Program and its integration and coordination. The Committee is designed to bring perspectives of the component science steering committees as well as expertise from the wider research community to overall ARCSS coordination and integration. Half of the AC members are ARCSS principal investigators; the remaining half represent the broad research areas addressed in the ARCSS Program but are not themselves ARCSS investigators. Specific AC responsibilities are:

- ⌘ to publish a periodic update of the ARCSS science plan;
- ⌘ to articulate criteria for setting priorities among the component themes and programs that will evolve as ARCSS proceeds, and to assist in setting and justifying those priorities;
- ⌘ to assist component programs and ARCSS in evaluating and reviewing the progress of each component, and in modeling and data management, toward the overall goals of ARCSS;
- ⌘ to serve as a conduit for new ARCSS community initiatives through its representatives and to assist in setting priorities among the emerging research themes and programs identified in new initiatives;
- ⌘ to assist ARCSS in developing synthesis, integration, and modeling studies; and
- ⌘ to facilitate integration of ARCSS component research to address ARCSS themes.

Community Coordination and Integration

With the advice of the ARCSS Committee, ARCUS has established an interactive site on the World Wide Web (WWW; see Appendices, page 39). Through these WWW pages, the ARCSS Committee hopes to promote discussions that lead to research addressing each of the five integrative questions listed in the Priorities chapter. The WWW site also conveys relevant information about the status of the ARCSS Program and provides links to other relevant sites.

Science Steering Committees

Each ARCSS Program component has or will have a science steering committee (SSC) acting as a clearinghouse for developing and prioritizing new initiatives, and a science management office (SMO) working with the SSC to coordinate community planning and implementation. The SSCs are made up of funded investigators and others in the relevant areas of research. When new initiatives are given a high priority, NSF (sometimes in conjunction with other federal agencies) publishes an Announcement of Opportunity (AO) seeking proposals from the general scientific community that address the goals of the AO. Responsibilities of each science steering committee are:

- ⌘ advising investigators on the objectives of the relevant component;
- ⌘ identifying gaps in the program;
- ⌘ recommending priorities for new program announcements;
- ⌘ suggesting and/or preparing input for the ARCSS science plan;
- ⌘ assisting in implementing and coordinating projects associated with individual components of ARCSS.

Periodic Meetings of ARCSS Principal Investigators

Periodic meetings of ARCSS investigators—within program components and for the overall ARCSS Program—serve a valuable integrating and planning function. In May 1996, the ARCSS Program convened the first ARCSS all-investigator workshop, bringing together members of the arctic system science community to determine the state of the overall scientific enterprise undertaken by ARCSS and to make recommendations for future research priorities. The 175 participants included principal and co-investigators, graduate students and post-doctoral researchers, and representatives of related programs. The resulting workshop report, *Toward an Arctic System Synthesis: Results and Recommendations* (In press), contains presentation abstracts and participants' recommendations for new directions in arctic system science.

Component investigator meetings, held more frequently, have a narrower scope or may be thematic. Many of these meetings will involve only subsets of the total pool of investigators. Proceedings of the investigator workshops should serve the needs both of the ARCSS Program and of individual investigators without imposing unreasonable additional reporting and publication burdens or competing with other important scientific meetings.

ARCSS Program Contact Information

Appendices

Arctic System Science Program

<http://www.nsf.gov/od/opp/arctic/system.htm>

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Greenland Ice Sheet Project Two (GISP2)

<http://www.gisp2.sr.unh.edu/GISP2/>

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Paleoclimates of Arctic Lakes and Estuaries (PALE)

<http://www.ngdc.noaa.gov/paleo/pale/index.html>

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Land-Atmosphere-Ice Interactions (LAI)

<http://www.laii.uaf.edu/>

LAI Science Management Office

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Ocean-Atmosphere-Ice Interactions (OAI)

<http://www.ccpo.odu.edu/~arcss/>

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OAI Science Steering Committee

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A History of ARCSS Program Development

- 1984** The U.S. Committee for the International Geosphere-Biosphere Programme (IGBP) developed a global change program that included the study of ice and snow, paleoclimate, and the polar regions; several members suggested that the Arctic could be a “test bed” for an integrated global change program in the United States and Canada. Between 1985 and 1988, members of the arctic research community briefed the National Science Foundation (NSF) and other national and international organizations on the importance of the Arctic in the global system and the value of an interdisciplinary arctic program as a developmental paradigm for global change science.
- 1987** Two workshops on the Arctic in Global Change were convened, and the results were published in *Arctic Interactions: Recommendations for an Arctic Component in the International Geosphere-Biosphere Programme (1988)*.
- 1988** In 1988, NSF funded the Arctic Research Consortium of the United States (ARCUS) to organize a follow-on workshop to implement the arctic interactions program; the concept of an **Arctic System Science (ARCSS) Program** was developed. The ARCSS initiative was established by NSF as a contribution to the U.S. Global Change Research Program with the Division of Polar Programs (DPP, now the Office of Polar Programs) as the lead division.
- 1989** Largely because of funding schedules, the implementation of ARCSS occurred at component and project levels. The already planned and funded **Greenland Ice Sheet Project Two (GISP2)** program was folded into the ARCSS Program along with a new program, **Paleoclimates of Arctic Lakes and Estuaries (PALE)**. These two programs deal with records of past climate change in the Arctic with emphasis on records of the last 2,000, 20,000, and 150,000 years. The Divisional Advisory Committee included both programs in the DPP Long-Range Science Plan with staggered start dates and suggested funding scenarios. The GISP2 drilling program began in 1989, and PALE was implemented in 1991. In subsequent negotiation, NSF’s Ocean Sciences Program assumed initial control of the oceans portion of the ARCSS Program.
- 1991** The ARCSS research community devised a management structure for the integrated ARCSS Program which included Science Steering Committees for the individual components and an oversight and integrating panel. As part of the developing infrastructure, ARCUS established the ARCSS Program Office in 1991 at the request of NSF and arranged planning meetings for the overall ARCSS Program and for LAII.

The two ARCSS programs implemented in the early 1990s concern modern interactions and processes—**Ocean-Atmosphere-Ice Interactions (OAI)** and **Land-Atmosphere-Ice Interactions (LAI)**. The Joint Oceanographic Institutions (JOI) organized workshops to develop a research plan for OAI; ARCUS did so for LAI. The results of these workshops were distributed to the scientific community for comment.

1991 (continued) JOI published *Arctic System Science: Ocean-Atmosphere-Ice Interactions* (1990). ARCUS published *Arctic System Science: Land/Atmosphere/Ice Interactions* (1991) and *Arctic System Science: Advancing the Scientific Basis for Predicting Global Change* (1990) and convened a meeting of agency representatives and others to present the program. JOI published the *Arctic System Science: Ocean-Atmosphere-Ice Interactions Initial Science Plan* (1992), and the first OAI projects were funded.

1992 NSF held the first LAII competition. Because the total cost of the interdisciplinary, integrated proposals greatly exceeded funds available, the NSF proposal-review panel selected certain portions to form an integrated but more limited Flux Study.

1993 The ARCSS Panel considered the conceptual structure and implementation strategy of ARCSS. ARCUS supported meetings to further define OAI, LAII, the LAII-Flux Study, and PALE. The composition and name of the ARCSS Panel were changed in 1995, following recommendations from an *ad hoc* ARCSS community working group advising on the community representation and advisory aspects of the panel's role. The panel became the ARCSS Advisory Committee and, later, simply the ARCSS Committee.

ARCUS began coordinating discussions and community planning for a research program on the human dimensions of the arctic system in 1993.

1994 NSF initiated Synthesis, Integration, and Modeling Studies (SIMS) in 1994. The ARCSS Committee developed recommendations for SIMS as a research emphasis within ARCSS in 1995 and published a community announcement for the 1 June 1996 NSF-OPP Arctic Research Program deadline.

1997 ARCSS has three linked ongoing components. Ocean-Atmosphere-Ice Interactions (OAI) and Land-Atmosphere-Ice Interactions (LAII) deal with modern interactions and processes among ocean, atmosphere, and ice, and among land, atmosphere, and ice, respectively. Paleoenvironmental Studies work with the records of past climate change in the Arctic, emphasizing the last 2,000, 20,000, and 150,000 years. This component is implemented through two projects: Paleoclimates of Arctic Lakes and Estuaries (PALE) and Greenland Ice Sheet Project Two (GISP2), administered within the Earth System History initiative of the United States Global Change Research Program. A research prospectus for a fourth component, *People and the Arctic: A Prospectus for Research on the Human Dimensions of the Arctic System (HARC)*, was published by ARCUS in 1997; announcements of opportunity are expected shortly for this component, which considers human activity as an integral part of the whole arctic system, both as a vital driver of climate change and as a link among the terrestrial, marine, and climate subsystems. ARCSS also supports the integration of research results across components and projects within ARCSS as well as with other arctic research programs through Synthesis, Integration and Modeling Studies (SIMS).

ARCSS Data Protocol

The National Science Foundation (NSF) Arctic System Science (ARCSS) Program supports a multidisciplinary research effort of the arctic environment. With the many different ARCSS data collection efforts, it is vital to facilitate data archival and an easy mechanism for data exchange among researchers interested in the arctic system. This data protocol is a guide for ARCSS investigators to ensure proper data formats, meta-data, and efficient data archival.

Data Management

Upon receiving a NSF ARCSS award, the Principal Investigator(s) (PI) will be contacted by the ARCSS Data Coordination Center to establish a data management plan. This plan will include procedures to migrate all data collected to the ARCSS archives. In addition, the Data Coordination Center will collaborate with the PI(s) on data information and formats. Individual project data migration plans will be updated yearly during the grant and for the years following project completion until all data resulting from the grant enters the archive.

Data Exchange

All data collected in the course of ARCSS-funded research is considered ARCSS community property. Principal investigators retain exclusive use of the data collected during the first year. After one year, data will be released to other ARCSS investigators. Two years after data collection, the data will be made available to all other science users through the ARCSS Data Coordination Center. Exceptions to these time frames will be referred to the specific ARCSS project Science Steering Committee or Science Management Office (SMO) and appropriate time period arrangements will be determined.

Data Set Referencing

Citation will be given to the investigators responsible for data collection in any and all papers using ARCSS data sets. References to these data will include:

- ① reference to papers describing the data;
- ② reference to the PI(s) if no papers are yet published;
- ③ reference to appropriate NSF grant numbers in the acknowledgments;
- ④ reference to ARCSS contribution numbers (if this program is developed); and
- ⑤ reference to the ARCSS Data Coordination Center Archive at the National Snow and Ice Data Center.

This information will be included with the meta-data associated with each data set.

Data and Information Formats

In coordination with the ARCSS Data Coordination Center, the PI(s) will include, at a minimum, the following information with each data set archived:

- ① collection dates;
- ② data collection methods;
- ③ data format (e.g., ASCII, Excel spreadsheet, ARC/INFO coverage, etc.);
- ④ data collection problems, data processing problems, bad data flags, data dropouts, and other quality control factors identified by the PI(s);
- ⑤ instrument descriptions and calibrations;
- ⑥ collection site descriptions and conditions; and
- ⑦ conditions for use and citation.

Data sets may have specific additional guidelines; the Data Coordination Center will work with ARCSS SMOs and the PI(s) to accommodate whatever special considerations are necessary. Data information sheets designed by the Data Coordination Center will help the PI(s) encapsulate this information and include it with the data when migrated to the long-term ARCSS archive. This information should take the form of a general Read Me document in ASCII text or a common word-processing file format.

Updates to the parameters listed above will be posted under Data Submission Guidelines on the ARCSS WWW site operated by the ARCSS Data Coordination Center at the National Snow and Ice Data Center (ARCSS Program Contact Information, page 39).

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This plan, an update of the first ARCSS science plan, *Arctic System Science: A Plan for Integration* (1993), examines the progress made in the last eight years, reviews significant research findings from each of the major programs of ARCSS, demonstrates the importance of integration and synthesis, and begins to define the questions and research priorities that now arise based on our increased understanding of the arctic system.

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