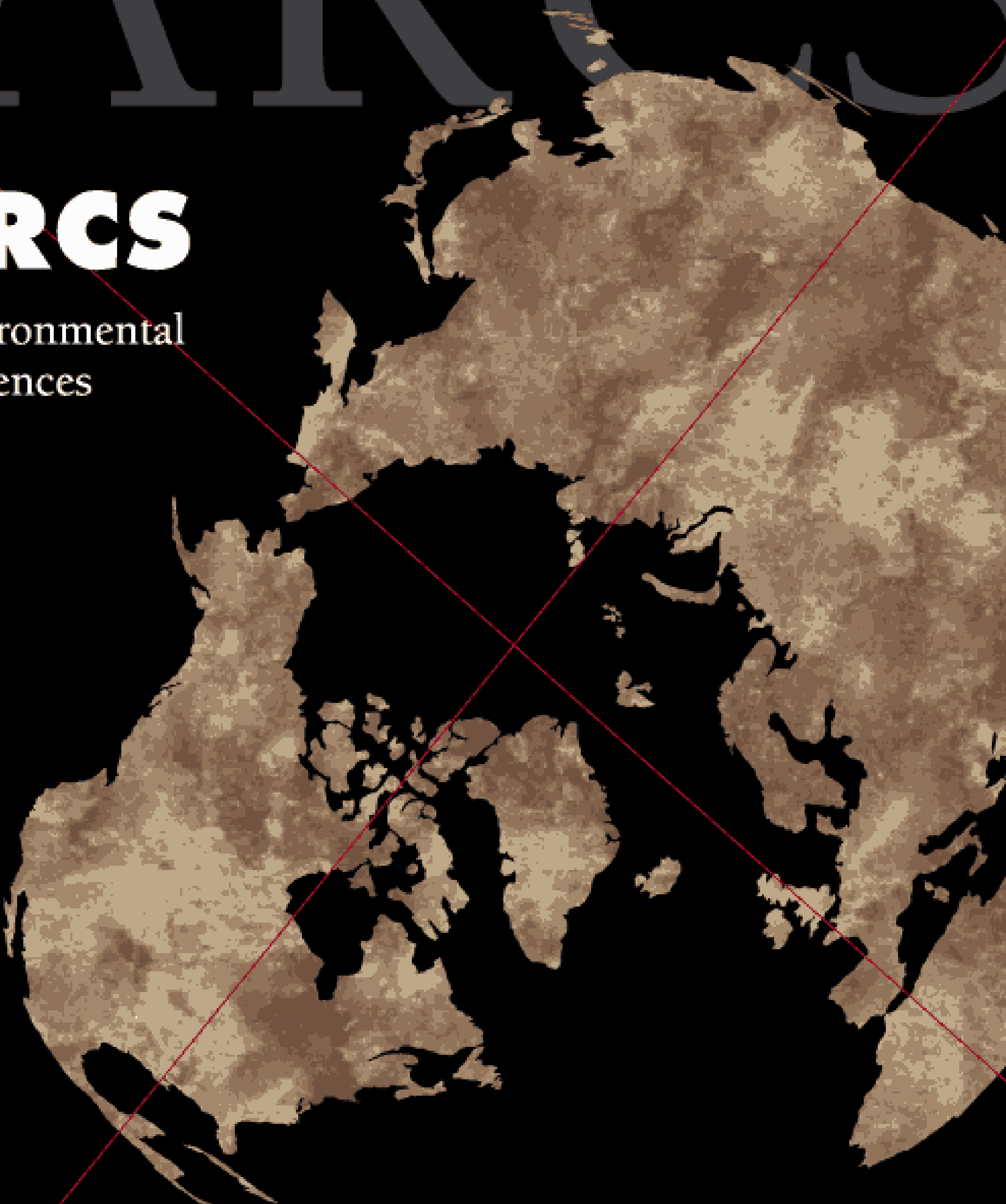
PARCS

THE ARCTIC PALEOSCIENCES IN THE CONTEXT OF GLOBAL CHANGE RESEARCH

# PARCS

## Paleoenvironmental Arctic Sciences



**Arctic System Science (ARCSS)Program**
**Earth System History (ESH) Program**

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# SUMMARY OF RECOMMENDATIONS

Over the last two decades a unified view of the Earth as an integrated system has developed within the scientific community. With the growth of this vision, effective research now requires much more than an *ad hoc* approach within the traditional disciplinary boundaries. A clearly defined organizational structure is required to demonstrate the commonality of purpose and to focus the energies of the research community. It is the purpose of this document to delineate research directions and an effective management structure that will enable the community's contribution to a more complete understanding of the Arctic's paleoenvironmental history and how arctic environmental processes are related to the global environment.

For the Arctic Paleosciences, the research community has developed an extremely demanding program of activities clustered around a series of major research imperatives. The imperatives are the central scientific issues posed by the challenge of the changing global environment. Each imperative is presented here in summary form and is elaborated by a series of scientific questions and recommendations for research.

### Imperative One

Describe and understand the range of natural environmental variability in the Arctic at temporal and spatial scales relevant to anticipating future change.

- Is the 20th century arctic and global warming unprecedented in the last 1000 to 10,000 years?
- What are the spatial-temporal modes of arctic seasonal to century-scale environmental variability? Are they predictable?
- How do major climate phenomena interact in the Arctic, and how have these interactions changed over time?
- Within the historical record, are hypothesized past climatic events (*e.g.* Little Ice Age, Medieval Warm Period) real and how do they relate to modes of Arctic variability? How are they recorded across the Arctic and what role did the Arctic play in driving these events? Do these events help explain the last 150 years of arctic change?
- What arctic climatic conditions are associated with more extreme levels of global warmth?

**Recommended research and research needs**

A high priority is to recover and synthesize a network of high-resolution paleoenvironmental records, including ice cores, tree rings, and lake and marine sediment cores.

Unraveling paleo-records is requires use of both multiple proxies and studies of modern processes to calibrate the various proxies.

To address questions relating to possibly even more extreme changes in the climate state that might be anticipated with further warming, longer term records, not necessarily at such high resolution, but with good spatial coverage, are required.

### Imperative Two

Evaluate the impact and cause of climatic “surprises” (*i.e.*, unexpected, extreme and/or abrupt events) in Arctic climate system behavior.

- To what extent is the extreme non-linearity of climate response, as seen in Greenland ice cores, due to feedbacks within the arctic ocean-atmosphere-cryosphere system?
- What is the role of volcanic eruptions in triggering climate change events, and specifically, changes that may extend beyond a few years?
- What is the role of the arctic hydrologic budget in influencing the large-scale overturning thermohaline circulation?
- What are the hydrologic and cyrospheric conditions leading into and during abrupt climatic change events?
- To what extent are salinity anomalies and associated changes in thermohaline circulation evident in marine and terrestrial paleoclimatic archives and do they serve as analogs for larger events in the more distant past?
- What changes, if any, occurred in sea-ice extent and biologic productivity within the Arctic Ocean basin and marginal seas during the major warmings observed in Greenland over the last 110,000 years?

**Recommended research and research needs**

Develop a series of 200-m length ice cores from around the Greenland Ice Sheet and the smaller ice caps in the circumarctic with an emphasis on paleoenvironmental analyses.

Develop and exploit proxy records from both terrestrial and marine sources to reconstruct sea-ice extent.

Develop proxies for evaluating past changes of the complete hydrological cycle including precipitation, river discharge and evapotranspiration variability.

Ensure that materials from ice cores, sediment cores and other archives that contain abrupt climatic change events are preserved so that the future development of new techniques to better assess these events can be pursued in a timely manner. Develop protocols for the use of these materials to ensure their preservation and availability.

### Imperative Three

Determine and understand the sensitivity of the Arctic to altered forcings - both natural and anthropogenic.

- How fast, and in what ways, do soils, permafrost, and vegetation respond to climate change?
- How fast, and in what ways, do arctic sea-ice and circulation respond to climate change?
- How fast, and what ways, do glaciers, ice caps, and ice sheets respond to climate change?
- What are the interrelationships between sea ice, arctic river runoff, and ocean circulation patterns?
- How have changes in arctic albedo affected earth energy balance and climate?

**Recommended research and research needs**

Within critical time slices, establish more certain estimates of the distribution and character of past sea-ice, land ice and thermohaline circulation. This should include the ice-free Arctic (ca. 2-3Myr) - how close are we now to an ice-free Arctic?

Document historic variations in terrestrial water balance and fresh water discharge to the Arctic Ocean.

Develop and evaluate proxy indicators of riverine water and dissolved and particulate matter input into northern seas. Maintain and further develop databases and models of river discharge, sediment load, and geochemistry for arctic watersheds.

Determine the formation, extent and variability of sea-ice cover on annual to millennial scales. Inquiry should consider entrainment and fate of biological and geochemical materials in sea ice.

Evaluate changes in sea level on the arctic shelves, including eustatic and isostatic factors, and resulting bathymetric evolution over the past 20,000 years. Information is needed on the co-evolution of river discharge foci, degradation of permafrost and changes in shelf currents with sea level variation. Use biotic and geochemical indices to quantify changes in water mass structure, circulation, and the distribution of biologic communities.

Encourage studies of modern processes that focus on the linkages between changes in watershed-to-shelf transport processes and primary productivity. Evaluate the spatial and temporal variability of biological productivity in estuary, delta, and shelf environments. Inquiry should focus on the natural states of productivity and potential response to environmental change.

Establish a geographically representative network of fossil pollen sites for the circumarctic and reconstruct past ice extents in order to calculate reasonable estimates of overall albedo change through the Holocene.

### Imperative Four

Document the history and controlling mechanisms of biogeochemical cycling of nutrients and radiatively active species.

- How can we reconstruct terrestrial nutrient flux in the past?
- How have changes in glaciers, permafrost, and other land-surface elements affected nutrient and sediment fluxes?
- Has the residence time of carbon in tundra soils changed over the last 10,000 years?
- What is the history of $CO_2$, $CH_4$ and $N_2O$ over the last 10,000 years and, in particular, over the last 1000 years?
- Can we reconstruct the history of water vapor in paleoenvironmental archives from the Arctic?
- How much of a role does the Arctic Ocean play in biogeochemical cycles? What is the role of the Arctic in the methane cycle?
- What are the mechanisms by which ice cores record the gaseous composition of the atmosphere?

**Recommended research and research needs**

Numerous well-dated, high-resolution records of atmospheric composition over the Holocene are needed. Despite their obvious importance in establishing pre-industrial behavior of key biogeochemical cycles, such records are lacking.

Encourage process studies of nutrient and sediment fluxes in arctic environments, with special focus on glaciers. These are needed for the calibration of proxy environmental indicators.

Recovery of radiocarbon-dated cores from extensive northern peatlands of Arctic North America and Eurasia to determine the history of carbon storage and the rates of sequestration. Collate global datasets on peat depth, accumulation history, carbon content, and carbon sequestration rates.

Development of proxies for nutrient fluxes into and out of arctic ecosystems. Information on past nutrient fluxes is essentially non-existent, yet nutrient availability is important, for example, in determining carbon photosynthetic and respiratory fluxes.

Exploit isotopic techniques to determine potential sources and sinks of methane during the Holocene and last glacial.

## Imperative Five

Evaluate the realism of state-of-the-art numerical models being used to predict future climate and environmental change on regional to global scales.

Can models reproduce the arctic temperature record on both temporal and spatial scales for ca. 400 years from reconstructed forcings of solar irradiance, volcanic inputs, and greenhouse gases?

Can models reproduce the known changes in the thermohaline circulation in the North Atlantic over the past 20,000 years, with inferred ice sheet and sea ice extent and fresh water inputs? How does the concomitant model-derived climate compare with proxy terrestrial records?

- What is the climate sensitivity during the Holocene to changes in arctic albedo associated with sea ice, sea level, and vegetation variability?
- Is model response to altered forcing (*e.g.* ice sheet extent, albedo, insolation) consistent with proxy evidence of the past changes in hydrology?
- How are hemispheric-scale changes in climate expressed at the regional to local scale and how do responses at these scales in turn feed back to the climate system?
- How well can we model climate-induced changes in lacustrine, fluvial, eolian, glacial, periglacial, ecological and other systems that may be impacted by climate change in the future?

**Recommended research and needs**

Time series of forcings for 400+ years of solar irradiance, volcanic input, and greenhouse gases.

Coupled climate model simulations for the time period AD 1600 to modern, testing individually and in combination the roles of internal feedbacks and forcing of solar irradiance, volcanism, and greenhouse gases on the climate of the Arctic.

Data of freshwater inputs (magnitude, duration, and location) for important periods (*e.g.*, 8.2 ka, Younger Dryas) over the last 20 ka.

Coupled climate simulations to understand the thermohaline circulation and its impact on the Arctic climate during the Last Glacial Maximum, Younger Dryas, and periods of freshwater inputs (*e.g.*, Heinrich Events and Dansgaard-Oeschger Cycles).

Regional climate model simulations of changing vegetation and sea level corresponding to conditions from the early Holocene to present.

Sea ice reconstructions and proxy development for the hydrologic cycle including precipitation, evapotranspiration, and river discharge. Sensitivity experiments with uncoupled and coupled climate models to test the sensitivity of the Arctic climate to sea ice extent and duration during the Holocene.

## Cross-Cutting Recommendations

Develop new or improve currently-used proxies that document past environmental conditions, with particular emphasis on sea ice extent and duration, the hydrological cycle, and atmospheric composition. Encourage rigorous proxy calibration and modern process studies.

Whenever possible, multi-proxy studies should be conducted to maximize the information retrieved from a study site and to provide mutually independent constraints on paleoenvironmental interpretation.

Success of the overall PARCS effort will depend to a considerable degree on the establishment of a rigorous chronstratigraphic framework. It is essential that dating control and age calibration of records from diverse depositional environments be improved for the correlation of multiproxy records throughout the Arctic. To this end, ready access to AMS-$C^{14}$ must be provided.

Improve or create networks of high quality marine or terrestrial records of various temporal resolutions from key regions, specifically the northern North Atlantic, northern areas of the Russian Federation, Greenland, northeastern Canada and the Canadian archipelago.

Examine possible mechanisms responsible for observed abrupt climatic changes on all time scales, glacial and interglacial.

Improve understanding of arctic carbon and water cycle dynamics during the late Quaternary.

Where appropriate, special attention needs to be focused on the influence of human activity on the environment, and the relationship of society and climate change.

Develop forward and process models on regional to global scales and at key times (*e.g.*, the last 400 years, the mid-Holocene, periods of abrupt change including the last deglaciation, and the last interglacial). Pay special attention to data-model intercomparison exercises.

Facilitate data archiving, distribution, syntheses, and paleoenvironmental reconstructions on regional to circumarctic spatial scales and various time scales. PARCS-generated data must integrate seamlessly with the PAGES/WDC-A and other global change programs.

Establish a simple and flexible administrative structure that will allow research energies to focus on the actual research effort. For US arctic research in the paleosciences, the centerpiece for this is PARCS (Paleoenvironmental Arctic Sciences), a new effort combining a number of smaller administrative units. Ensure that this effort integrates well within the current Federal agency structure and coordinates closely with international efforts (*e.g.* PAGES/IGBP).

# FOREWORD

Effective global-scale research requires a clearly defined organizational framework through which a community of scientists may focus their energies. This intellectual and managerial structure frames the overarching questions and objectives, identifies the essential and most promising avenues of research and, if well conceived, preserves the community's flexibility to address the unexpected result. It is the purpose of this document to delineate an effective management structure and research directions that will enlarge our understanding of past changes in the Arctic environment, to understand better how those changes in the Arctic are related to the global environment, and to contribute to our ability to predict and respond to future changes.

This document, a "science and implementation plan", has been prepared by the scientists engaged in paleoenvironmental research of the Arctic. It is a community effort designed to recognize the enhanced role of the paleosciences within the Arctic System Science (ARCSS) Program, and to firmly place the Arctic paleoscience research agenda within the global framework of the Earth System History (ESH) Program. The document briefly summarizes the background and research highlights accomplished over the last decade. In the light of these accomplishments, and with a new appreciation of the urgency and complexity of the global change problem, it is appropriate for the community to review the current status of knowledge, consider alterations in course, and explore new avenues of research.

The product of two community meetings, and with the consideration of a broad representation of Arctic researchers, this document provides guidance from the community to the community. It reformulates essential research questions concerning Arctic paleoscience within the context of global environmental change, points out the most promising research directions and strategies for the near future, and provides a flexible management structure for the implementation of these strategies.

# INTRODUCTION

## The Global Change Research Act of 1990

The recognition that society was causing changes in the biology, physics and chemistry of the environment on regional and global scales prompted the U.S. Government to establish the U.S. Global Change Research Program (USGCRP). This Program was designed to carry out a coherent, integrated plan to document, understand, and assess the impact of these environmental concerns and the scientific issues posed by the Earth's changing environment (NRC, 1998). The U.S. Congress enacted the Global Change Research Act of 1990 to meet the need for a better understanding of the natural variability of the Earth's global environment and the effects of human activity. The Act calls for an integrative research effort "aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment…"

The research elements identified in the Act are:

- Global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales.

- Documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades.

- Studies of earlier changes in the Earth system, using evidence from the geological and fossil record.

- Predictions, using quantitative models of the earth system to identify and simulate global environmental processes and trends, and the regional implications of such processes and trends.

- Focussed research initiatives to understand the nature of and interaction among physical, chemical, biological, and social processes related to global change.

The USGCRP is coordinated across 10 Federal agencies with the goal to establish the scientific basis for national and international policy making related to natural and human-induced changes in the global system. The U.S. science-funding agencies work together to develop research activities that respond to one or more of the following general focal areas of research:

- To observe and document changes in the Earth system
- To understand why these changes are occurring
- To improve predictions of future global changes
- To analyze the environmental, socioeconomic, and health consequences of global change
- To support state-of-the-science assessments of global environmental change issues.

### Earth System History (ESH), Arctic System Sciences (ARCSS)

In support of these global change efforts, the National Science Foundation (NSF) established the Earth System History (ESH) and Arctic System Science (ARCSS) Programs as research elements of the USGCRP. These programs include coordinated multidisciplinary efforts directed towards the application of the paleosciences to global change issues.

ESH is a research initiative that includes coordinated paleoscience programs supported by several divisions of the NSF and NOAA's Office of Global Programs. ESH contributes to understanding global change by focusing on critical elements of the coupled atmosphere-biosphere-cryosphere-earth-ocean system (ESH, 1995). The goal of ESH research is to understand the natural variability of the Earth system through records preserved in geo-biologic archives and contribute to a comprehensive understanding of environmental change with annual to millennial resolution, including the forcing mechanisms, interactions and feedbacks among its components.

ARCSS is supported by the Office of Polar Programs (NSF). The primary challenge of the ARCSS Program is to determine how the arctic environmental system functions and to establish its role in global change (ARCSS, 1993). The ARCSS Program was initiated in the late 1980's as a community effort to develop a system approach to arctic environmental research within the USGCRP. ARCSS was conceived as a series of coordinated process-oriented components that dealt with Land-Atmosphere-Ice Interactions (LAII) and Ocean-Atmosphere-Ice Interactions (OAII). These components are primarily directed towards understanding modern arctic environmental process. From its inception, the arctic research community recognized that a full understanding of the arctic system on societal-relevant timescales required a systematic effort to understand the changing environment in the time dimension. Two large paleoscience projects focused on the Arctic: the Greenland Ice Sheet Project (GISP2) and Paleoclimate of Arctic Lakes and Estuaries

(PALE). These were adopted as the initial elements of the Paleoenvironmental Studies component of ARCSS. More recently, additional components have been developed within ARCSS - the Human Dimensions of Arctic Change (HARC) and a new Synthesis, Integration, and Modeling Studies (SIMS) effort was initiated to promote research that integrates across components. The goals of ARCSS are:

- 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

- To advance the scientific basis for predicting environmental change on a decadal to centuries time scale, and for formulating policy options in response to the anticipated impacts of changing climate on humans and societal support systems.

## Paleoenvironmental Arctic Sciences (PARCS)

Paleoclimate research straddles both the ARCSS and ESH Programs, and paleoenvironmental research activities in the Arctic have expanded to include all facets of the paleosciences. In recognition of this, the ARCSS and ESH Programs have coordinated their efforts into a new overarching effort - Paleoenvironmental Arctic Science (PARCS). The Arctic possesses a rich archive of evidence for changes in the environment on a variety of time scales. The importance of the Arctic, and polar regions in general, was noted in reports of the National Research Council (NRC, 1984, 1998). Subsequently the history of the Arctic System was identified as a major goal in ARCSS (1993, 1998), specifically to provide a longer baseline against which to measure ongoing changes in the arctic landscape and to gain a deeper understanding of the role and impact of the Arctic in Global Change.

Close cooperation among scientists of many nations is a basic necessity for understanding global change in the Arctic and for achieving the research goals of ESH and ARCSS. Past Global Changes (PAGES), an IGBP core project, acts as a self governing body for identifying research problems of highest importance for the international paleoscience community. Clearly, the strong ties that ESH and the Paleoenvironmental Studies component of ARCSS have already established with PAGES/IGBP will be strengthened by the broader scope of research encompassed by PARCS. To insure compatibility of research results and to coordinate data management activities among numerous projects and scientists, research protocols developed by PAGES are utilized in several sections of the PARCS science plan.

*Earth history* is as vital to society for planning and forecasting environmental factors, as *human history* is in understanding national and international politics. We need to know through what extremes the natural Earth system has varied in the past in order to fully grasp what future global change scenarios might entail. We cannot, nor should we, make future predictions of the Earth system without a thorough understanding of both present and past modes of environmental variability. Because the arctic system is predicted to be highly sensitive to changes in climate forced by the atmosphere's rising concentration of greenhouse gases, it is necessary to establish whether paleo-records from arctic archives, (such as tree rings, ice cores, lake, peat and marine deposits, and historical accounts) also document similar past changes with increased amplitudes within the Arctic.

These studies constitute an important contribution to the global change assessment activity - charting the socioeconomic implications of climate change for people's well being. Assessments of the impact of climate change are essential to policy and management decision making; they encourage the formulation of policy options in response to the anticipated impact of climate change. Although assessments related to particular problems are occurring, no comprehensive integrated regional impact assessment has been undertaken of the Arctic and the assessment exercise is an essential overarching goal of the ARCSS Program. PARCS will contribute to the assessment activity by providing the historical perspective, an understanding of the natural environmental variability, and an appreciation of the inter-relationships of natural and anthropogenic systems.

## WHY THE ARCTIC?

The Arctic is recognized as a crucial region for studying global change. Sensitive indicators of change are reflected in its biota, snow and ice features, and short- and long-term climactic and atmospheric history is stored in permafrost, ice sheets, biological materials, 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.

Paleoenvironmental research has taught us that the Arctic has experienced some of the greatest environmental swings of any region on Earth, and hence the geography and ecology of the Arctic have also undergone vast changes. During periods of glaciation, most of the world's unstable ice sheets existed in this region—the Arctic was home to the gathering grounds and the centers of spread for the Laurentide, Fennoscandian, and Eurasian Ice Sheets. The growth of these ice sheets caused sea level to fall and the subsequent melting of these ice masses contributed approximately 90 meters of the 105 meters of the global sea level rise experienced at the end of the last period of glaciation (Peltier, 1994, 1996). The growth and disappearance of these ice sheets is associated with changes in the incoming solar radiation at the critical northern latitude of 65°N (Hays *et al.*, 1976; Imbrie *et al.*, 1992). However, recent research has demonstrated that the pace of change of the climate system also includes several intervals of rapid and abrupt change—episodes of massive ice sheet collapse, such as the Heinrich-events (Andrews, 1998; Bond *et al.*, 1992; Broecker, 1994; Broecker *et al.*, 1992) which cannot be attributed to, or predicted by, variations in incoming radiation.

Arctic and subarctic biomes have contracted and expanded during the Quaternary, reflecting fluctuating conditions associated with repeated glacial cycles. For example, many arctic regions that were covered by ice, polar desert, or herb tundra during the last Glacial Maximum now support boreal forest (Lamb and Edwards, 1988; Ritchie, 1987). Variations in the spatial distribution of these northern biomes impact regional- to hemispheric-scale climate systems through, for example, changes in albedo and surface roughness (Foley *et al.*, 1994 ). Such changes in vegetation also affect soil and permafrost characteristics, which, in turn, influence biogeochemical processes (Bonan and Shugart, 1989; Van Cleve *et al.*, 1983), and impact the waters of the productive Arctic Ocean shelves. Paleoenvironmental studies in the North have shown regionally complex vegetation histories with individualistic responses of key arcto-boreal taxa to climactic change (Anderson and Brubaker, 1994; Webb, 1988; Huntley and Birks, 1983). Consequently, it is unlikely that the response of arctic-subarctic vegetation to future climates will be a simple, circumarctic displacement of intact modern plant communities.

Glacial-interglacial sea level changes are associated with large fluctuations in the extent of the marine shelves bordering the coasts of Siberia, Alaska, and NW Canada and in patterns of freshwater input to the Arctic Basin. Such changes strongly affect ocean circulation and the productivity of coastal waters. On shorter time-scales, dynamics of the arctic climate has forced significant changes in the nature of ocean circulation and potentially in the climate at lower latitudes. The "Great Salinity Anomaly" of the 1960s (Dickenson *et al.*, 1988; Mysak and Power, 1991; Serreze *et al.*, 1992) has been attributed to changes in freshwater and sea ice flux from the Arctic Ocean into the Greenland and Labrador Seas. This recent example highlights the significant role that the Arctic plays (Aagaard *et al.*, 1991; Aagaard *et al.*, 1985) in the global thermohaline circulation – "the Achilles' Heel of the climate system" (Broecker, 1997).

## THE ARCTIC AS A PALEOENVIRONMENTAL ARCHIVE

The Arctic hosts a great diversity of paleoenvironmental archives, and some of the longest and most detailed records have been retrieved from the Arctic. Ice cores, laminated lake sediments, and tree rings typically have annual resolution across different periods of time. Silled fiords with anoxic basins are also potential sites for annual laminae. Records with decadal to centuries resolution exist in the form of lake sediment, peat deposits, and marine sediments from fiords and shelf-troughs, as well as slope and deep-sea abyssal plain locations.

Ice core records have been a central focus of arctic paleoscience research over the last two decades. Although deep coring in Greenland has recovered startling records in terms of the abruptness of change in the climate system, it is important to note that smaller polar ice caps in other areas of the Arctic offer opportunity of developing a network of coring sites and thus the possibility of evaluating paleoclimatic spatial gradients (Alley *et al.*, 1993; Fisher *et al.*, 1998; Fisher *et al.*, 1995; Johnsen *et al.*, 1992; Koerner and Fisher, 1985; Taylor *et al.*, 1993).

Lake sediments, like ice cores, yield continuous records of change, but in contrast to the ice cores, lake records are widely distributed throughout the Arctic and thus provide insight into the variability of regional responses to global climate forcings (PALE, 1995). The current circumarctic network of lake sites, although still sparse in many regions, generally allow for century scale reconstructions of past conditions and landscapes. Other terrestrial deposits, such as peats, with similar temporal resolution provide important complementary paleoenvironmental information to the lake records. Because much of northeastern Asia and northwestern North America remained ice-free during glacial times, ancient lake records of Marine Isotope Stage (MIS) 6 or older age, provide continuous records of environmental change over two glacial-interglacial cycles (Berger and Anderson, 1994; Brubaker *et al.*, 1995). Additionally, lakes from ice-free areas can help in defining margins of former ice sheets and in describing the history of glaciation and deglaciation (Steig *et al.*, 1998). Records of paleolimnological indicators and lake-level studies can reveal past changes in hydrological conditions and moisture balance (MacDonald *et al.*, 1993; Barber and Finney, in press). Annually laminated sediments have proved to be a valuable source for describing changes over the last 2000 year in the Canadian Arctic, Labrador, Iceland, and Greenland (Anderson *et al.*, 1985; Donner *et al.*, 1994; Hugen *et al.*, 1994; Overpeck, 1996). Such lakes are important complements to other high-resolution records preserved in ice cores and tree rings.

Tree rings, like lake and peat deposits, are an important source of paleoenvironmental data applicable to local and broader spatial analyses. Northern treeline has always been an important marker, both as the boundary between the Arctic and Subarctic regions and as an indicator of summer temperature. Dendrochronological research in some treeline areas has extended knowledge of tree growth variations several hundred to as many as 2000 years into the past (Jacoby and D'Arrigo, 1989; Briffa *et al.*, 1990, 1995, 1998; D'Arrigo and Jacoby, 1992; Wiles and Calkin, 1993; Szeicz and MacDonald, 1996; Overpeck *et al.*, 1997).

Continuous sedimentary records of the late Quaternary are sparse on shallow continental shelves at lower latitudes. In contrast, the arctic shelves include deep, glacially eroded troughs and nearshore basins, such as fiords. Thus Arctic nearshore and shelf environments often possess long records of changes (100 to 30 cm/Ky rates of sediment accumulation) in the marine environment with decadal to century-scale resolution and preserve evidence of changes in oceanographic conditions and in patterns of iceberg rafting (Andrews *et al.*, 1991, 1995, 1996, 1997; Jennings and Weiner, 1996; Lubinski *et al.*, 1996; Polyak *et al.*, 1995, 1997).

The deeper Arctic marine sedimentary environments, such as the slopes and deep-sea plains, also retain evidence of significant changes in Arctic oceanography and climate. Much of the early research within the Arctic Ocean concentrated on the longer Neogene history (*e.g.* Clark, 1990b). This vast area, however, has only provided a multi-millennial record of past changes that are poorly linked to records outside the Arctic (Jones, 1987; Morris, 1988; Darby *et al.* 1989). Later coring expeditions have sought to retrieve records with higher rates of sediment accumulation which document changes over the last few marine isotope stages (Andrews *et al.*, in press; Hald and Aspeli, 1997; Hald and Hagen, 1998; Stein *et al.*, 1994, 1996; Phillips and Grantz, 1997). Most recently, researchers have focussed on arctic environmental changes since the last glacial maximum, where powerful tools such as accelerator mass spectrometer $^{14}C$ dating can be brought to bear (Darby *et al.*, 1997). This work indicates that millennial-scale records can be found in the central Arctic Ocean and these should help in establishing the paleoenvironmental history of this ocean.

# ACCOMPLISHMENTS

It became evident over the past decade that if we were to understand the long-term interactions of human society with the environment, a new concept of coordinated, multidisciplinary projects would be required to address the planet as a system. Many of these projects were initiated in the last decade, and they have made a discernible difference in the way we view the Earth and the Arctic. Individual projects and collective efforts, (*e.g.*, GISP2 and PALE) by U.S.-based scientists have contributed significantly to this multiproxy approach to the study of the arctic system. During the course of these projects, strong individual and group ties were established within the international community (*e.g.*, GISP2-GRIP, PALE-PACT, PALE-CAPE, the Beringian working group of U.S., Russian, and Canadian scientists). These research links will form the foundation for continued cooperative arctic research under PARCS. The following outline does not include all the scientific efforts of arctic scientists within the past decade, but it highlights some of the more recent accomplishments of the arctic research community.

**Solar Forcing**

Particularly exciting results from high-resolution ice cores include the observation that many geochemical and atmospheric dust parameters show strong spectral power at frequencies close to or identical to those observed in the sun. Remarkably, the time-series are coherent not only in phase, but also in amplitude, providing what is probably the best evidence to date for the elusive solar-climate relationship.

**The Record of Atmospheric Chemistry**

One consequence of the increase in world population and industrialization is the increase in atmospheric $CO_2$, $CH_4$, and nitrous oxide ($N_2O$). The first direct measurements of these trace gases were begun in 1957. Prior to this, the world's ice sheets constitute the best archive of the record of atmospheric composition. The record of these greenhouse gasses has been reconstructed from measurements of the trapped gases in ice. To date, the results show a doubling of $CH_4$, a 25% increase in $CO_2$, and a 10% increase in atmospheric $N_2O$ concentrations above baseline pre-industrial levels. There is little doubt that the majority of the increase in all three species is related to the increase in human population and the accompanying industrialization and land use stress over the last two centuries.

**Biomass Burning**

Paleoclimate records have shown that widespread biomass burning can have a significant effect on the chemistry of the atmosphere and biogeochemical cycles as a whole. Records reflect variability in biomass burning of the Northern Hemisphere, subarctic regions of Canada, and Alaska. Establishing the past record of these burn events allows the evaluation of the relationship between climate conditions and the frequency of large-scale fires.

**Extreme Volcanic Events**

Ice cores provide the best means for determining the potential atmospheric impact of explosive volcanic activity. Volcanic events, recorded in the Greenland ice core sulfate series, correlate with annual changes in atmospheric temperature, providing evidence for sulfate aerosol shielding and for evaluating past variability within the volcanism-climate system. Ice core records have shown that the number of eruptions capable of perturbing climate over the last 110,000 years is far higher than previously thought. Findings from the GISP2 ice core suggest that the Toba eruption occurred 71,000 years ago, was the largest volcanic eruption of the last 500,000 years, and may have been a driving force leading to several centuries of cold climactic conditions. Should such an eruption occur today, it would have a tremendous impact on human society. Hemisphere scale tree ring networks can yield valuable information on geographic variability of response to these events (Jacoby and D'Arrigo, 1992; Briffa *et al.*, 1998, D'Arrigo and Jacoby, 1999).

**The History of Annual Temperature**

A recently published synthesis of past climate change in the Arctic (Overpeck *et al.*, 1997) has demonstrated that the arctic environment has undergone large changes during the last four centuries (Figure 4). Thermometer records from the Arctic are scarce and shorter in length than records at lower latitudes, but they do indicate that the Arctic has warmed about 0.6°C since 1910 and include a significant warming trend from the late 1970s to the present. Since 1860, proxy data reveal that the average surface temperature in the Arctic has increased by 1.5°C with warming in some locations approaching 3.0°C. This has been twice the average warming for the Northern Hemisphere. The proxy data also indicate that the magnitude and extent of the arctic warming over the past 150 years are unprecedented when compared to climate records extending back through much of the last 1000 years.

Where thermometer and proxy records overlap in time, the records are in good agreement. When the relatively short thermometer record of the 20th century is compared to proxy temperature data spanning the last few centuries, it becomes clear that the 20th century is not at all representative of the average conditions of this millennium. Before society input significant amounts of greenhouse gasses into the atmosphere, natural (pre-industrial) arctic temperatures were, on average, 1°C colder than during the 20th century, with a variation of about 0.5°C. When the centuries-long record of Arctic temperature variation is compared to reconstructed records of candidate climate forcing mechanisms (Figure 1), it appears that solar/volcanic variations can explain much of the climate's natural variability. However, this does not hold for the post-1920 warming. This observation agrees with climate theory and modeling, which suggests that arctic warming in the 20th century is increasingly dominated by human influences (*i.e.* greenhouse gasses). Evidence is accumulating that this warming trend commenced in the mid-nineteenth century (Jacoby and D'Arrigo, 1989), as part of pattern of temperature change over recent centuries that is seen in the heart of Eurasia as well as in the Arctic (Jacoby *et al.*, 1996).

**Fluctuations in Arctic Ocean Surface Circulation**

Studies of ice rafted detritus (IRD) have shown that the surface dispersal patterns and thus circulation have changed dramatically in the western Arctic Ocean during glacial/deglacial events (Bischof and Darby, 1997). Proshutinsky and Johnson (1997) have proposed that the Beaufort Gyre may reverse itself on decadal time-scales.

**Rapid Climate Change Events**

One of the most dramatic recent contributions to our understanding of paleoclimate during the last glacial cycle has come in our recognition of sub-millennial scale climate variability. Unprecedented swings in the Earth's climate over sub-decadal to millennial time scales have now been recorded in the GISP2 and GRIP ice cores from central Greenland. This has instigated new, higher resolution, investigations of land and marine paleoclimate records.

The millennial scale events recorded in the last 110,000 years of the two central Greenland ice cores are unequivocally climate events. They represent large climate deviations (massive reorganizations of the ocean-atmosphere system) that occur over decades or less. During these excursions, large changes have occurred in surface temperatures and in the rate of snow and wind-blown dust accumulation (Cuffey *et al.*, 1995). These changes occurred within decades to as little as a single year (Johnsen *et al.*, 1992; Alley *et al.*, 1993; Taylor *et al.*, 1993; and Mayewski *et al.*, 1993). There is also evidence that the ocean's thermohaline circulation changed in step with the Greenland excursions (Keigwin and Boyle, in press). These climate deviations seem to have been largest during the transitions into and out of the glacial maximum. Smaller amplitudes are seen during the glacial and interglacial maxima (Severinghaus *et al.*, 1998), but because the millennial signal can be traced from glacial to interglacial times it is known that the underlying process is pervasive (Keigwin and Jones, 1989; Bond *et al.*, 1997).

**Natural Climate Variability During the Holocene**

High-resolution, continuous Holocene paleoclimate records from the GISP2 ice core and other sources show complex annual to millennial variability. A prominent cooling event at about 8200 years ago has a dry, windy, low-methane "fingerprint" in regional to hemispheric records that is similar to abrupt changes during the glacial period (Alley *et al.*, 1997). This event punctuated the Holocene record of northern temperature, which was similar to, or warmer than, the modern record. This occurrence demonstrates that a glacial climate is not a required pre-condition for such widespread climactic events. Other significant Holocene climate changes lack this "fingerprint", suggesting that much spatial complexity has characterized the Holocene Arctic.

**Arctic System Modeling**

The use of fully-coupled atmosphere-ocean-sea ice climate models and the development of high-resolution regional models for the Arctic represent major innovations for advancing our understanding of the dynamic arctic environment. Although some biases still occur in arctic sea ice extent (Weatherly *et al.*, 1998; Bromwich and Briegleb, 1998), fully-coupled models show significant improvements in simulation of arctic sea level pressure and precipitation-minus-evaporation over previous GCM simulations. Arctic processes are sufficiently modeled to generate seasonal, interannual, and decadal variability and to understand potential feedbacks affecting long-term perturbations in the climate state.

Significant progress also has been made in model-data comparisons for the last 21 ka (Bartlein *et al.*, 1998) using simulations from atmospheric GCMs. Coupled climate model simulations of past climates are in their preliminary stages with a fully-coupled CSM simulation for 6 ka (Otto-Bliesner, 1998; 1999) and an EBM atmospheric model coupled to the GFDL ocean model for the Last Glacial Maximum (Weaver *et al.*, 1998). Insights from GCM-paleodata comparisons have also aided the development of conceptual models, which are valuable for developing an interpretive framework or paleoclimatic hypotheses for times lacking GCM simulations (Bartlein *et al.*, 1991).

Regional climate models provide the capability of modeling precipitation and temperature patterns that are dependent upon topographic and coastal details not resolved by the coarse resolution global climate models. Lynch *et al.* (1995) first developed a regional climate model for Beringia, and has since expanded the simulation to include the entire arctic basin (Maslanik, personal communication).

Dethloff *et al.* (1996) and Rinke *et al.* (1997) have also simulated the arctic basin with a regional model. No paleoclimate simulations of the Arctic have yet been completed with a regional model.

**The Beringian Virtual Atlas**

Another major regional synthesis is the “Paleoenvironmental Atlas of Beringia,” (Figure 12) which describes the climate and environment of Beringia over the last 21,000 years. The Web site is: http://www.ngdc.noaa.gov/paleo/pale/atlas/beringia/index.html. The atlas is a living document that is periodically updated as new data or data syntheses are contributed, thereby providing the most up-to-date results from the region. Atlas users have access to both primary (*e.g.*, pollen counts) and value-added (*e.g.*, inferred vegetation) paleoenvironmental data that are available in spreadsheet, mapped, time series and/or movie format. It is intended to broaden the scope of the atlas by encouraging and facilitating other regional working groups to implement their own geographic modules, which ultimately can be combined to form a circumarctic atlas. The atlas will be a central tool for data-climate model comparisons and will provide state-of-the-art documentation of the spatial and temporal patterns of change during the late Quaternary throughout the Arctic.

# RESEARCH IMPERATIVES

The ensuing discussion of research challenges follows the outline of *Research Imperatives and Scientific Questions* as presented in "Global Environmental Change - Pathways for the Next Decade" (NRC, 1998). This research framework for the USGCRP is constructed in terms of primary topical areas and is here adapted to address the arctic paleosciences in relation to global change. Research Imperatives are the central scientific issues posed by the challenge of the changing global environment.

It is not surprising that these imperatives also reflect the research directions addressed through the ARCSS Program (ARCSS, 1998) and are noted as ARCSS "priorities for the future":

- How will the Arctic climate change over the next 50 to 100 years?
- How will human activities interact with future global change to affect the sustainability of natural ecosystems and human activities?
- How will changes in arctic biogeochemical cycles and feedbacks affect arctic and global systems?
- How will changes in arctic hydrologic cycles and feedbacks affect arctic and global systems?
- Are predicted changes in the Arctic detectable?

These arctic-focussed approaches are needed to achieve a fundamental understanding of the arctic environmental system through synthesis and integration across a wide spectrum of temporal and spatial scales. Each Research Imperative is elaborated by a set of scientific questions and a set of requirements or recommendations for research activities that together form the intellectual framework of this endeavor. We note that the formats for these imperatives are not identical and, in some cases, there is overlap in the broadly-defined topical boundaries. We ask the reader's forbearance – separate writing teams prepared these sections which are designed to be self-consistent and to make the clearest presentation for the topic being addressed.

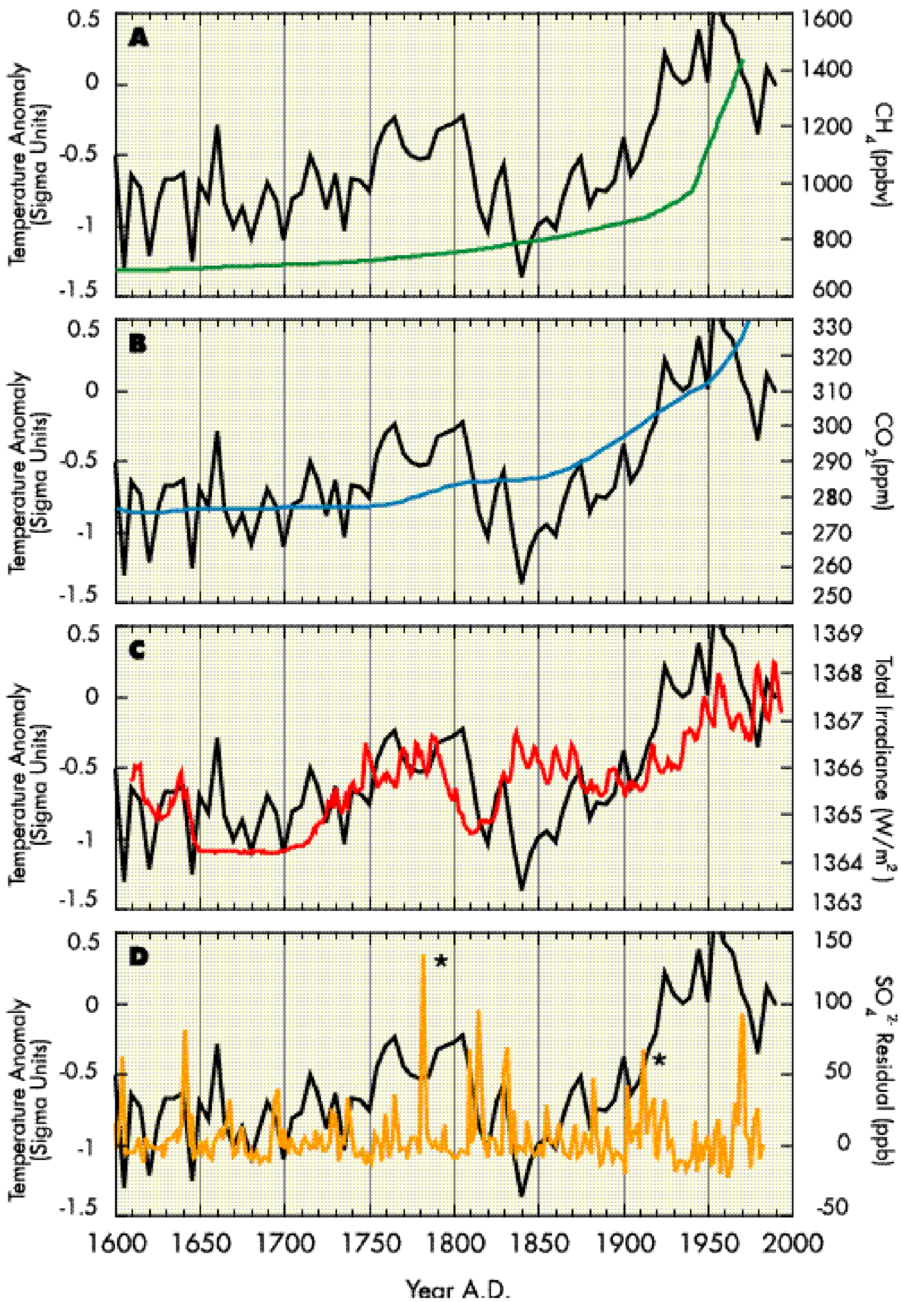
## Imperative One

**Describe and understand the range of natural environmental variability in the Arctic at temporal and spatial scales relevant to anticipating future change.**

There is an urgent need for circumarctic reconstructions that can be used to understand the dynamics of temporal and spatial environmental changes in the Arctic. Excepting the Antarctic, the region is the least inhabited or environmentally disturbed on Earth, but may also be one of the most sensitive to natural and human-induced environmental changes. The observational record of arctic environmental change is short and geographically sparse. For example, very few climactic stations exist with records extending back beyond 50 years. Those that do extend to the beginning of the 20th century suggest that the Arctic has warmed by about 0.6°C, with temperatures peaking around 1945 at 1.2°C more than in 1910 (Chapman and Walsh, 1993). This observed arctic temperature increase is greater than that of the Northern Hemisphere as a whole, and indicates an amplification of global climate change in the region. However, there is also evidence of significant regional variability in observed arctic temperature changes. Between 1966 and 1995 most arctic regions have warmed by 0.2°C to 1°C per decade, while the area extending from the east coast of Hudson Bay to the west coast of Iceland has cooled by as much as 1°C due to dynamics within the North Atlantic Ocean (Chapman and Walsh, 1993).

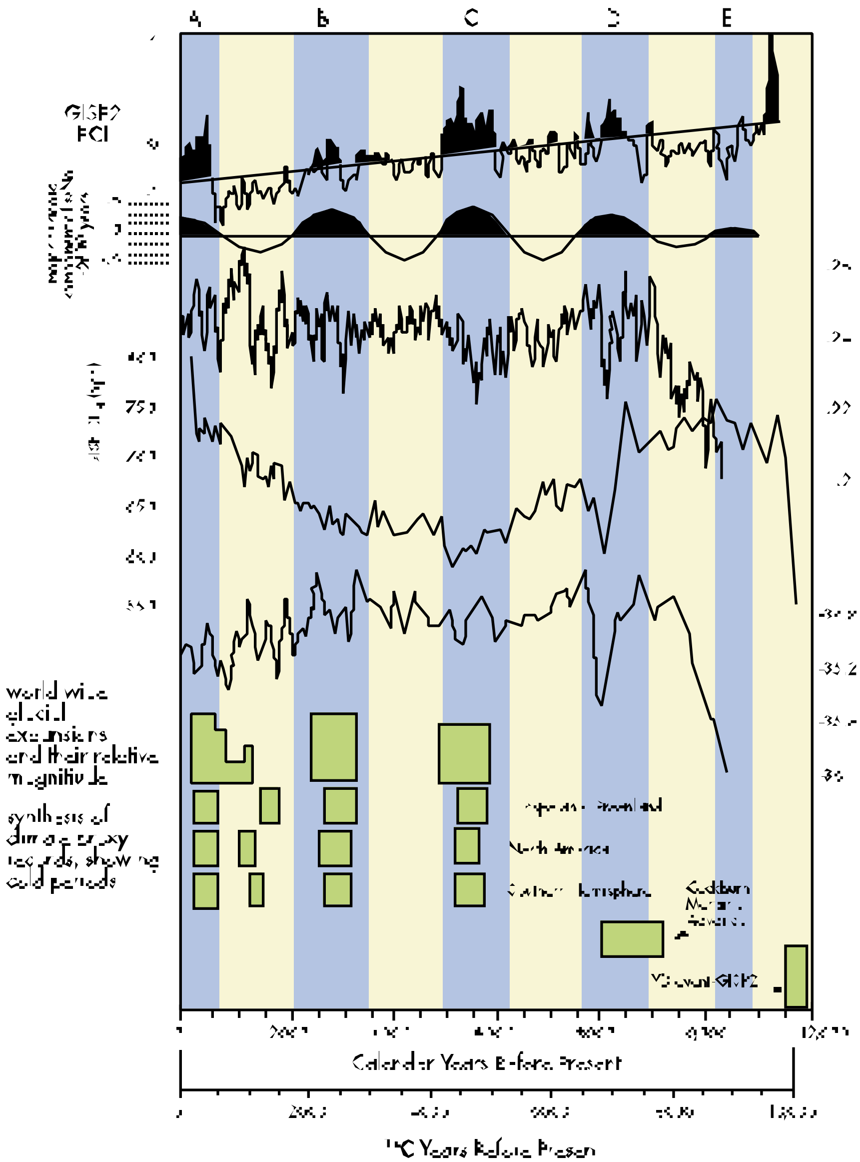
Although the observational data provide evidence of significant temporal and spatial variability in recent arctic environments, the records are too short to identify the full potential range of variations that the Arctic has experienced in the past or may experience in the future. Paleoenvironmental records of past arctic changes are the only means of extending our records back in time and increasing their spatial coverage in order to describe and understand the full range of temporal and spatial variability in the arctic environment. For example, how unique is the warming that has been detected at most Arctic regions over the course of the 20th Century? Paleoenvironmental data collected from a network of lakes, wetlands, tree-ring sites, ice cores and marine sources demonstrate that both the magnitude and spatial extent of 20th Century arctic warming may be unprecedented over the past 400 years (Overpeck *et al.* 1997). However, understanding the exact causes of this warming remains difficult. It may be related to a combination of natural factors such as changes in solar irradiance and volcanic aerosols in the atmosphere or other unknown forcing which occurs on millennial time scales, or it may be related to anthropogenic factors such as increased greenhouse gasses (Figure 1).

The environmental variability of the last 400 years is superimposed



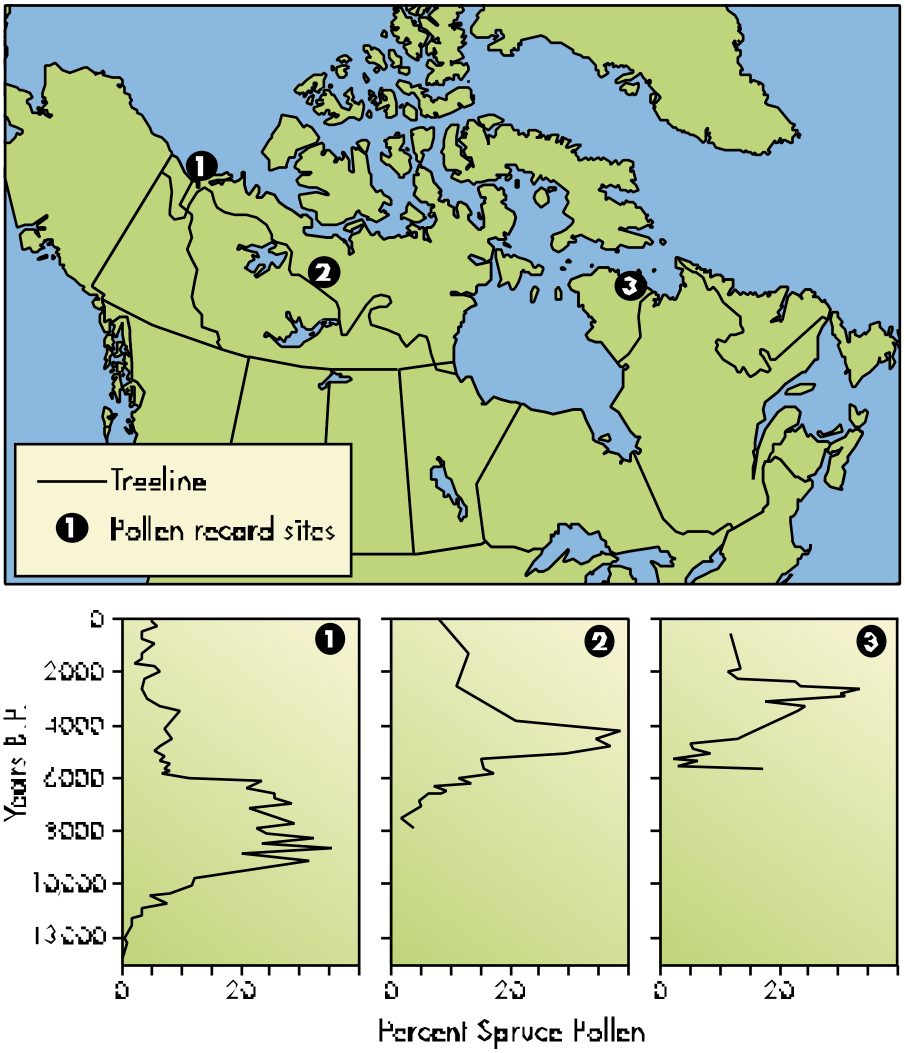

1. Comparison of hypothesized external climate forcing (colored lines) and standardized proxy Arctic-wide summer-weighted annual temperature (gray lines, plotted as sigma units) for: (A) atmospheric $CH_4$, (B) atmospheric $CO_2$, (C) solar irradiance, and (D) Greenland (GISP2) ice core volcanic sulfate. Eruptions known to be over-represented in the GISP2 record are marked with an asterisk (after Overpeck *et al.*, 1997).

on longer-term changes that have occurred over the Holocene (the last 10,000 years). Evidence from Greenland ice cores suggest that the Arctic may have experienced a pattern of rapid climactic changes occurring with 1450 to 1800 year periodicities (Figure 2). How such changes impacted different regions of the Arctic is unknown at present. Most of the Arctic experienced summers significantly warmer (1 to 2°C) than in recent centuries during the early to middle Holocene (10,000 to 4000 BP), due to greater summer insolation at high northern latitudes caused by changes in the orbital geometry of the Earth. However, the time and




2. GISP2 annually-dated Holocene EOF1, a proxy for Northern Hemisphere polar cell intensity (also referred to as the PCI, Polar Circulation Index) smoothed with a robust spline (equivalent to a 100-year smooth) with a quasi-2600-year periodicity (O'Brien *et al.*, 1995); GISP2 accumulation rate (Meese *et al.*, 1994); GRIP methane (Blunier *et al.*, 1995); GRIP del$^{18}$O record (Dansgaard *et al.*, 1993); worldwide glacial expansions and their relative magnitude (Denton and Karlen, 1973); synthesis of various climate proxy records from Europe, Greenland, North America, and the Southern Hemisphere showing cold periods (Harvey, 1980); the Cockburn Stade (Andrews and Ives, 1972; Alley *et al.*, 1997; Stager and Mayewski, 1997) and the Younger Dryas event (Alley *et al.*, 1993; Mayewski *et al.*, 1993). Letters specify major cold periods with 'A' equal to the Little Ice Age (after Ice Core Working Group, 1998).

duration of greatest warming differed geographically because of the effects of regional synoptic circulation anomalies, local sea-surface temperatures (SSTs), and land-ice cover. The spatial variability of this warming is clearly traced in the northern North America fossil pollen records. The paleovegetational data show that boreal forest was found north of the modern treeline between 10,000 and 5000 BP in western Canada, 5000 and 4000 BP in central Canada, and 4000 to 2000 BP in eastern Canada (Figure 3; MacDonald and Gajewski, 1992), whereas in Alaska Holocene treeline never expanded beyond its modern limit (Anderson and Brubaker, 1994).




3. Change in spruce pollen from small lakes located north of the present Canadian treeline indicates that the boreal forest has extended slightly further north than present. However, the timing of this northward extension varies with longitude. The treeline is associated with the mean July position of the arctic front; regional variations in treeline position may relate to position of the front which is controlled by a number of internal and external factors (after MacDonald and Gajewski, 1992).

It is clear from existing observational and paleoenvironmental records that the Arctic has experienced significant environmental variations at different temporal and spatial scales. Such variations, driven by natural and anthropogenic factors will undoubtedly occur in the future. Understanding the nature and causes of such variations is fundamental to understanding the arctic environment. The use and development of new paleoenvironmental techniques and data sets to describe and understand the causes of the temporal and spatial variability that is evident in the Arctic is an important goal for future arctic research.

**Is the 20th century arctic and global warming unprecedented in the last 1000 to 10,000 years?**

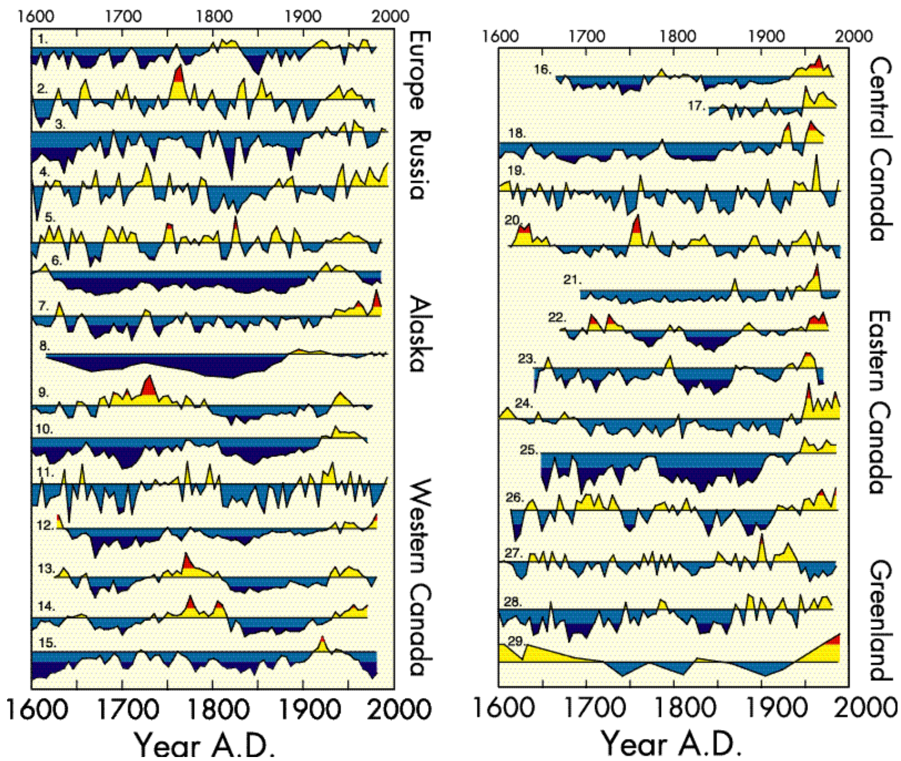
Environmental changes in the Arctic during the 20th century are unprecedented with respect to the past six centuries (Overpeck *et al.*, 1997, Briffa *et al.*, 1998, Mann *et al.*, 1998). Overpeck *et al.* (1997) estimate that approximately 50% is unrelated to natural forcing factors, while Mann *et al.* (1998) also show the changing importance of natural and anthropogenic factors at the onset of the twentieth century (Figures 1, 4). It is less clear whether this warming is unique over longer periods of the Holocene. The next challenges are to determine whether such change has occurred due to natural forcing within a longer time frame, and to increase the geographic resolution of environmental proxy records.

**What are the spatial-temporal modes of arctic seasonal to century-scale environmental variability? Are they predictable?**

The instrumental and paleoclimate records indicate that distinct "modes" or "states" of variability, often separated by abrupt transitions characterize the full range of climate variability. For example, the Pacific basin, extending to the high-latitudes, experienced a shift in variability mode in the mid-1970's (Proshutinsky and Johnson, 1998). Using the paleoclimate record, a much larger number of climate modes become apparent as longer periods of time are considered. The many abrupt shifts in climate state during the last glacial period are now well known from arctic paleoclimate research (cf. Taylor *et al.*, 1993; Mayewski *et al.*, 1993). It now appears that the present Holocene interglacial was also likely characterized by multiple distinct modes of variability (Meese *et al.*, 1994; O'Brien *et al.*, 1995; Bond *et al.*, 1992; Keigwin and Jones, 1989; Keigwin, 1996; Jennings and Wiener, 1997). A key challenge to the arctic research community is to develop the detailed observational basis and theory to understand the full range of modes of environmental variability in the Arctic, how they relate to climate states at lower latitudes, and determine the degree of predictability of these modes.

**How do the major recognized climate phenomena interact in the Arctic, and how have these interactions changed over time?**

The climate research community has identified major climate phenomena within the annual to century-scale, each affecting large portions of the globe and perhaps containing some elements of predictability. These include: the North Atlantic Oscillation (NAO), the Pacific-North American pattern Oscillation (PNA), the Arctic Oscillation (AO), and the El Niño-Southern Oscillation (ENSO). In some cases, (*e.g.*, the NAO and associated AO), there are clear arctic manifestations of these phenomena. In other cases (*e.g.*, ENSO), there are clear arctic




4. (A) Standardized 400-year proxy climate records reflecting surface air temperature for sites from Arctic Europe east to western Canada. Red indicates temperatures greater than one standard deviation warmer than average for the reference period (1901-1960), whereas dark blue indicates at least one standard deviation colder than this average. (B) Sites in Canada east to Greenland. All series are presented as 5-year averages except for sites 8 and 29, which are plotted at their original lower resolution. All time series represent surface temperature except for site 29, which represents SST. All time series are available at [http://www.ngdc.noaa.gov/paleo/paleo.html] (after Overpeck *et al.*, 1997).

teleconnections, but these have not been well studied. Most importantly, we already know from paleoclimatic work at lower latitudes that the variability and teleconnections associated with all these phenomena varies significantly in time, and with altered climate forcing. A priority in arctic paleoenvironmental research must be to understand how the major modes of recognized climate variability interact in the Arctic and how these interactions change over time, and with respect to changed forcing.

**Within the historical record, are hypothesized past climactic events (*e.g.* Little Ice Age, Medieval Warm Period) real and how do they relate to modes of Arctic variability? How are they recorded across the Arctic? If so, what role did the Arctic play in driving these events? Do these events help explain the last 150 years of arctic change?**

In the Arctic as elsewhere, there has long been evidence for widespread decadal to century-scale features in Holocene climate. It has been difficult to assess their extent and intensity because only a few records of limited geographical distribution were available (Hughes, 1995) and the chronology of these records was not always well established. Improvement on both these fronts has taken place in recent years, with the development of several hundred high quality time series for the Arctic. These provide the bases for circumarctic, hemispheric, and even global spatiotemporal reconstructions of climate at annual resolution for recent centuries (Briffa *et al.*, 1998; Overpeck *et al.*, 1997; Mann *et al.*, 1998, in press; Jones *et al.*, 1998). They reveal rich patterns of behavior in the space, time and frequency domains, whose detailed exploration has only just commenced. This exploration must include the interpretation of the seasonal and annual maps of climate variables in terms of climate dynamics, so that mechanistic relationships can be hypothesized and tested. Events such as the Little Ice Age may now be put in the context of this fuller record, especially as it is extended to cover the last millennium, and then the last two millennia. The spatial information produced in these reconstructions will be invaluable in disentangling possible mechanisms leading to particular patterns of variation (Rind and Overpeck, 1993), and in examining the role of the Arctic in driving these larger-scale effects. This is an essential stage in explaining the climate of the last 150 years.

**What climactic conditions are associated with more extreme global warming, which may occur in the next century?**
The transition from glacial to interglacial mode at the end of the last glaciation saw extremely rapid rates of warming, which in turn led to rapid adjustments in northern hemisphere ice sheets and a meltwater-generated cooling (see Imperative 2). Furthermore, during MIS 5, which saw global and arctic regional temperatures ca. 2-3°C higher than present (and thus is a possible temperature analogue for predicted anthropogenic warming), a considerable reduction in the size of the Greenland ice cap is postulated, and ice extent in the Arctic Ocean may have been greatly reduced (see Imperative 3). The environmental conditions experienced by marine and terrestrial ecosystems at these times differed greatly from those of the present. It is not impossible that such conditions could be achieved in the near future, and thus further study of the paleoenvironments of these periods is a high priority.

**Essential research for understanding temporal and spatial variability of arctic paleoclimate**

- A high priority will be to recover and synthesize a network of high-resolution paleo-environmental records, including ice cores, tree rings, and lake and marine sediment cores. To address the questions of the significance of the 20th Century warming, the occurrence of events such as the Medieval Warm Period and the Little Ice Age, and the assessment of the longer-term variability of distinctive phenomena (such as the NAO), there is a need for detailed proxy records spanning *at least* the last 2,000 years (IGBP, 1992) over a spatial scales that will allow for detection of regional variability. Circumarctic studies will build on several hundred existing records, primarily from tree rings and lake sediments developed by workers from many countries. Several >1000-year annually resolved temperature records already exist for the Arctic (Briffa *et al.*, 1992, 1995; Hantemirov, 1995; Hughes *et al.*, in press; Nuarzbaev and Vaganov,1998). These are predominantly from Russia, and there is a need to strengthen the 1000-year proxy-network in North America in order to provide a definitive answer to this question. Studies of regional phenomena (NAO, AO) will require strategically situated transects or networks of ice cores, tree rings and sediment cores to address the temporal-spatial variability of the paleoclimatic signal represented in the proxy records. At key sites, the high-resolution studies will be extended to span the Holocene (past 10,000 years). These data will increase our understanding of the range and amplitude of past changes in the arctic climate system relevant to future changes.

- Unraveling the paleo-records is accomplished through use of both multiple proxies and the study of modern processes to calibrate the various proxies. The value of using multiple proxies allows for dense spatial coverage across the Arctic from treeline to the high Arctic. Some paleoclimatic interpretations (ice-core-gas isotopes, borehole thermometry) are calibrated against the laws of physics, but various types of proxy evidence of past environmental change (*e.g.* varves, pollen, diatoms, foraminifera, chrinomids, and stable isotopes) are calibrated by comparison with modern climatological, limnological, or oceanographic data or by qualitative assessment of modern processes and ecological assemblages. Recognition of variability highlighted by various paleoenvironmental proxies over time also require the development robust geochronological frameworks utilizing state-of-the art dating methods at high sampling resolution intervals.

- Growing evidence for abrupt and unprecedented ecological change in the last century is found in many arctic archives (*e.g.*, Douglas *et al.*, 1994) and highlight ongoing ecological change. At the finer spatial and temporal scales of investigation, ecosystem characteristics that affect resource use and subsistence, such as fire frequency and fish populations dynamics, can be examined (HARC, 1997). To address questions relating to possibly even more extreme changes in the climate state that might be anticipated with further warming, longer term records, not necessarily at such high resolution, but with good spatial coverage, are required.

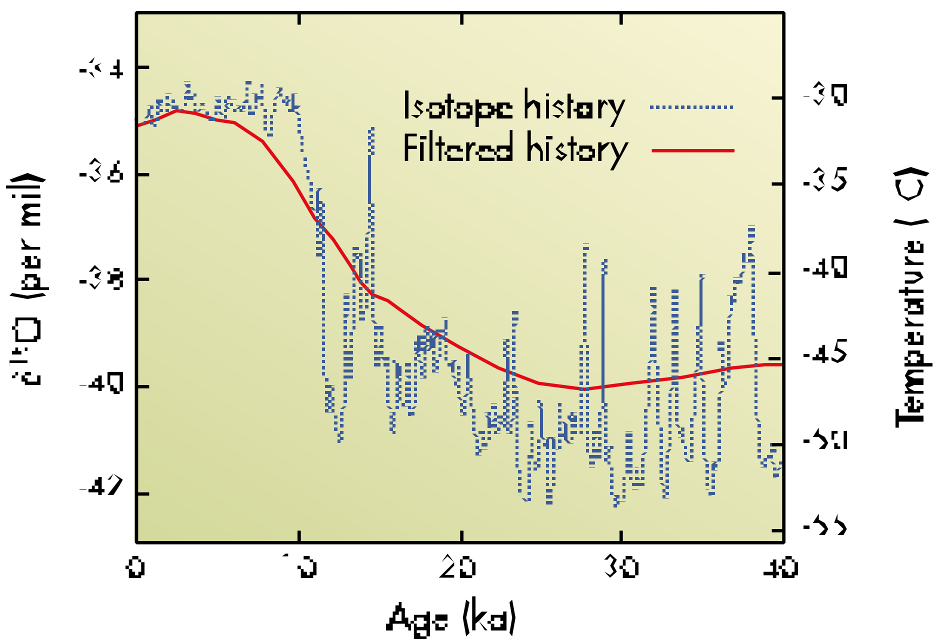
## Imperative Two

### Evaluate the impact and cause of climactic "surprises" (*i.e.*, unexpected, extreme and/or abrupt events) in Arctic climate system behavior.

Unanticipated and unprecedented swings in the Earth's climate over sub-decadal to millennial time scales have now been recorded in two ice cores from central Greenland (Ice Core Working Group, 1998). This has instigated new, higher resolution investigations of land and marine paleoclimate records. The millennial scale events recorded in the last 110,000 years of the GISP2 and GRIP ice cores are unequivocally major environmental events that include changes in temperature (Figure 5), atmospheric circulation, dust loading and greenhouse gas content, and snow accumulation. They are typified by large temperature swings (10-20°C) that occur over decades or less (Alley *et al.*, 1993; Taylor *et al.*, 1993; Mayewski *et al.*, 1993; Johnsen *et al.*, 1992; Cuffey *et al.*, 1995; and Alley and Clark, in press).

Evidence of similarly large and abrupt changes in temperature has been recovered from deep marine sediment cores from the North Atlantic especially during the quasi-periodic Heinrich events (Heinrich, 1988). Apparently correlative environmental changes are noted as far afield as western North America, South America, China, and Antarctica. The amplitude of temperature variation associated with these events appears to be largest in the circum-Atlantic region. However, additional potential ice coring sites and long lake, bog, and marine records located within the Arctic, but outside the limits of the last glaciation, have been largely under-exploited for the study of these events. In consequence, we do not yet know whether the large-amplitude temperature swings documented in the Summit ice cores are characteristic of the entire Arctic region, nor whether feedbacks operating solely within the Arctic contribute to the amplitude of the observed signal. In addition, the environmental response of the Arctic to the abrupt swings in temperature has yet to be determined.

Examples of rapid change originating within the Arctic are available from the instrumental record and are also recoverable from sediment, ice core and tree ring archives. For example, the "great salinity anomaly" (Figure 6) appears to have been associated with anomalous freshwater discharge in the central Arctic, sea ice transport to the open Atlantic, and ultimately associated with reduced ventilation in the Greenland Sea (Mysak and Power, 1991; Dickenson *et al.*, 1988). This chain of events may have been similar to conditions leading up to the dramatic climactic swings documented in ice cores. In addition, evidence is growing from tree-ring and other data for an extensive intense cold period in the decade beginning AD 540 (Baillie, 1994).

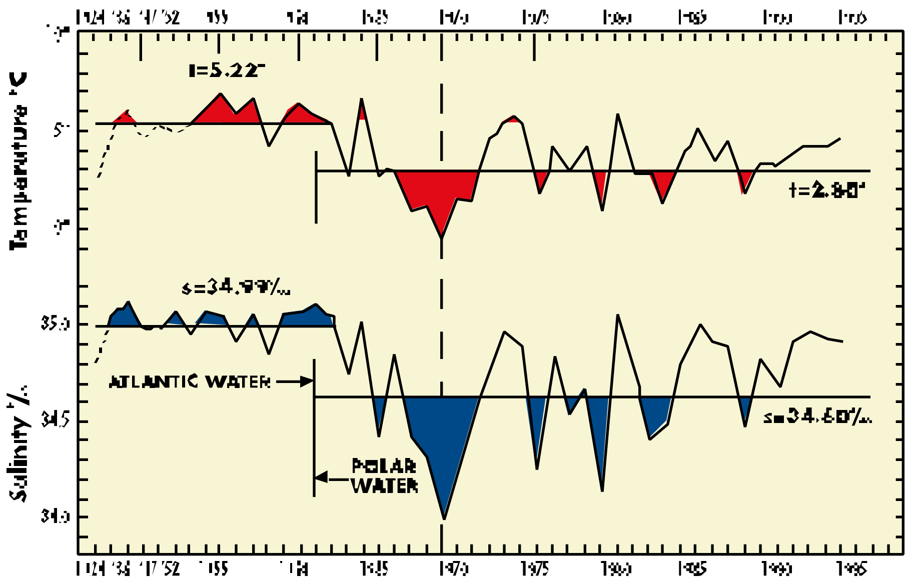



5. The central Greenland del $^{18}O$ history for the most recent 40,000 years. The smooth curve results when this history is filtered to mimic the thermal averaging in the ice sheet. All temperature histories that give this same curve when filtered are indistinguishable to borehole thermometry. The right axis shows the calibrated temperature scale (after Cuffey *et al.*, 1995).

Although based initially on Irish oaks, this phenomenon has recently also been observed in tree rings from the Taimyr Peninsula and northern Yakutia (Nuarbaeve and Vaganov, 1998) and as far south as the Sargasso Sea.

In addition to these complex and abrupt changes in climate, other high magnitude/low frequency events can cause drastic changes in climate that may last several years to decades or even to centuries. The environmental effects from such events may have the greatest potential impact on human society. Perhaps the most obvious of these are explosive volcanic eruptions (high-sulfur, climatically-effective eruptions; Angell and Korshover, 1985; Rampino *et al.*, 1988); other types of events, such as biomass burning, also play a role on time frames that impact our socio-economic condition.

Although the time frame of the impact from volcanism is generally on the order of only a few years, multiple eruptions, closely spaced in time, can reduce average temperatures on decadal time scales (*e.g.* Zielinski, 1995; Briffa *et al.*, 1998). Moreover, mega-eruptions, such as the Toba eruption of ~73,000 years ago (Rampino and Self, 1992, 1993; Zielinski *et al.*, 1996), may alter the global climactic system for several centuries through complex feedback mechanisms. Most importantly, the impact of such events becomes amplified in the Arctic. The low sun angle compared to other latitudes enables greater reflection and




6. Changes in the 50-meter temperature (upper curve) and salinity (lower curve) along a transect north of Iceland (average values for stations along the Siglunes transect) from 1924 to 1994. Note the rapid shift in water characteristics in the 1960's probably associated with the "Great Salinity Anomaly" (after Malmberg, 1985).

absorption of incoming solar radiation by these volcanically produced stratospheric aerosols. Following an explosive, high-sulfur producing eruption, the resulting temperature depression of 1-2°C at high latitudes may be an order of magnitude greater than the average global decrease in temperature of 0.2-0.3°C. Cool summers can produce positive feedback through an enhanced albedo that results from prolonged seasonal snow cover and positive mass balance of glaciers (Bradley and England, 1978).

Different styles of volcanism under different climactic modes will impact the potential range of variability in the volcanism-climate system. A chronology of the magnitude and frequency of volcanism and all other phenomena (*e.g.* biomass burning events, major synoptic-scale storms) that may play a role in forcing variability in insolation, biogeochemical cycles, hydrological cycles, and other aspects of the Arctic ecosystem needs to be established to enhance predictive capabilities.

Questions

- To what extent is the extreme non-linearity of climate response, as seen in Greenland ice cores, due to feedbacks within the arctic ocean-atmosphere-cryosphere system?

- What is the role of volcanic eruptions in triggering climate change events, and specifically, changes that may extend beyond a few years?

- What is the role of the arctic hydrologic budget in influencing the large-scale overturning thermohaline circulation?

- What are the hydrologic and cyrospheric conditions leading into and during abrupt climactic change events?

- To what extent are salinity anomalies and associated changes in thermohaline circulation evident in marine and terrestrial paleoclimatic archives and do they serve as analogs for larger events in the more distant past?

- What changes, if any, occurred in sea-ice extent and biologic productivity within the Arctic Ocean basin and marginal seas during the major warmings observed in Greenland over the last 110,000 years?

**Recommended research and research needs**

- Develop a series of 200-m length ice cores from around the Greenland Ice Sheet and the smaller ice caps in the circumarctic (*i.e.*, PAGES-ICAPP) with an emphasis on paleoenvironmental analyses.

- Develop and exploit proxy records from both terrestrial and marine sources to reconstruct sea-ice extent.

- Develop proxies for evaluating past changes of the complete hydrological cycle including precipitation, river discharge and evapotranspiration variability.

- It is essential to correlate all types of well-dated records across the Arctic. It must be assured that dating control is rigorous so that records from different proxies may be cross-dated at a resolution that will allow evaluation of abrupt climactic change events.

- Ensure that materials from ice cores, sediment cores and other archives that contain abrupt climactic change events are preserved so that the future development of new techniques to better assess these events can be pursued in a timely manner. Develop protocols for the use of these materials to ensure their preservation and availability.

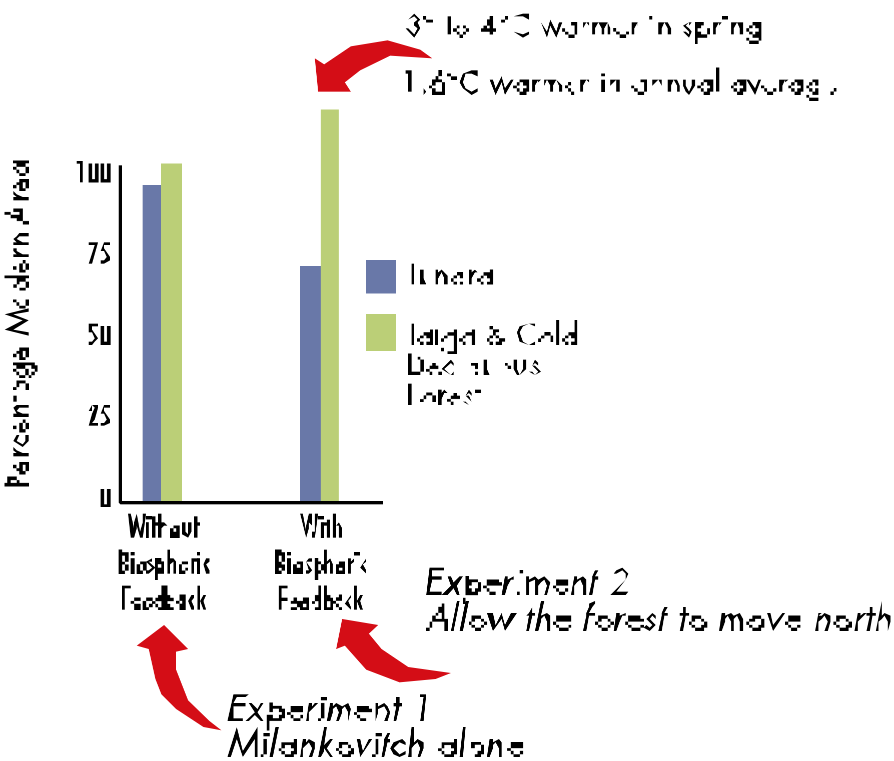
## Imperative Three

### Determine and understand the sensitivity of the Arctic to altered forcings - both natural and anthropogenic.

The most recent consensus (Houghton *et al.*, 1996) is that a greenhouse gas increase equivalent to a doubling of atmospheric $CO_2$ concentrations will warm the Earth by between 1.0 and 3.5°C. This uncertainty depends, to a large extent, on how sensitive the climate system is to a given amount of forcing. Climate sensitivity, in turn, depends on the sign and magnitude of feedback processes that serve to amplify or dampen the direct radiative effect of the given forcing. Most estimates (*i.e.*, simulations) of future change indicate that warming will be amplified in the Arctic relative to lower latitudes. This enhanced arctic climate sensitivity stems from a number of positive climate feedbacks, including melting of ice and snow that decreases surface albedo, atmospheric stability trapping temperature anomalies near the surface, and/or cloud dynamics which magnify change (Houghton *et al.*, 1990; Chapman and Walsh, 1993; Curry *et al.*, 1996). Although satellite and instrumental observations can be used with modeling studies to estimate the size of these and other feedback effects, there is only one way to know if arctic response is realistic in the face of altered climate forcing - we must look to the past when radiative climate forcing was different from today. And, because the Arctic is highly sensitive to climate change, it is an excellent natural laboratory for the study of sensitivity and environmental response to climate forcing.

**How does the paleoenvironmental record clarify our understanding of the character of key arctic climactic feedback processes, including: oceanic, biospheric and cyrospheric?**

Combined paleoclimatic observational and modeling studies have demonstrated that many of the forcing and feedback mechanisms incorporated in state-of-the-art climate models are estimated to the correct order of magnitude (Lorius *et al.*, 1990, Wright *et al.*, 1993). For example, we can simulate the general magnitude of millennial-scale climate change since the Last Glacial Maximum (Webb and Kutzbach, 1998). However, we are only now beginning to get reliable quantitative estimates of past climactic conditions in the Arctic and recent efforts to simulate past Arctic change indicate that some important feedback processes are not yet realistically simulated. Foley *et al.* (1994) and TEMPO (1996) have highlighted the need to include more realistic vegetation and associated biophysical feedbacks in arctic models of (Figure 7). Kerwin *et al.*, (1998) demonstrates that the lack of realistic oceanic (*e.g.* sea ice and thermohaline) feedback has led to an inability to simulate the full magnitude of past arctic climate sensitivity.




7. Simulated 6ka climate and biome feedback (after Foley *et al.*, 1994).

**How fast, and in what ways, do soils, permafrost, and vegetation respond to climate change?**

In a variety of paleorecords, we can now identify changes in treeline position (Anderson and Brubaker, 1994; Kremenetski *et al.*, 1998). It is clear from these records that both the expansion and retreat of treeline was not uniform. Analysis of paleoenvironmental data from a network of sites particularly in Beringia (northwestern Canada, Alaska and eastern Siberia), has revealed regional and sub-regional environmental responses to large-scale climate controls (Lozhkin *et al.*, 1993; Anderson and Brubaker, 1994; Anderson *et al.*, 1996; Edwards *et al.*, in press). These spatially heterogeneous but climatically consistent responses have been examined in light of the modern linkages between synoptic-scale atmospheric circulation features and surface-climate responses (Mock *et al.*, 1998). Vegetative responses are also directly linked to changes in permafrost and soil moisture characteristics as a part of this complex system. Despite evidence that permafrost terrains across parts of the arctic are changing rapidly under the present warming trend (Osterkamp and Romanovsky, 1996; Hinkel *et al.*, 1996), we have little information how permafrost was impacted in the past under different climate regimes or what feedbacks are associated with such changes (Oechel and Vourlitis, 1994; Oechel *et al.*, 1993). The large amounts of carbon that are sequestered in Arctic soils and permafrost have the potential to stimulate a positive climate feedback if released due to warming.

**How fast, and in what ways, do arctic sea-ice and circulation respond to climate change?**

Instrumental and satellite observations do not provide a sufficient observational basis to evaluate how well digital models estimate the sensitivity of arctic sea ice and circulation under altered climate forcing. We have in the paleoenvironmental record of the Arctic, however, a resource that may be used to examine many of the decadal- to millennial-scale processes that impact this fundamental part of the climate system. The arctic paleoenvironmental record provides the opportunity to compare simulated responses with sensitivity observed for past periods under climate forcing significantly different from today.

Studies of past interglacial periods, such as Marine Isotope Stages (MIS) 5 and 11, allow us to better understand and quantify oceanographic and sea ice responses to warmer-than-present climate scenarios. For example, during the last interglacial MIS 5e, when sea level was at least 6 meters above present, winter sea ice limits in the Bering Strait region were 800 km further north than now - leaving the Bering Sea and Strait ice free the year around (Brigham-Grette and Hopkins, 1995). At the same time, treeline limits were several hundred kilometers further north than at present in western Beringia (Lozhkin and Anderson, 1995). And yet, paleotemperature estimates for MIS 5e indicate that mean arctic temperature was only 2-3°C warmer than now. Given projections for our future climactic system, will arctic sea ice retreat to a similar extent? Some have speculated that such climate conditions may have driven the interglacial collapse of large ice sheet systems (*e.g.*, Greenland or the West Antarctica Ice Sheets). The modern thinning of Arctic sea ice and warming of the Atlantic layer in the Arctic Ocean, as documented by the SHEBA project (McPhee *et al.*, 1998), gives us startling information on the rapidity of the response of the modern Arctic to recent warming. Dramatic improvements in our reconstructions of past Arctic environmental changes should help us to strengthen our understanding of the forcing behind these changes and to better clarify many key climate feedback mechanisms that are related to sea ice and oceanographic conditions in the Arctic Ocean.

**How fast, and what ways, do glaciers, ice caps, and ice sheets respond to climate change?**

Terrestrial and marine-based study of the growth and decay of glaciers and ice sheets is a fundamental part of the global change program. Over the last decade, knowledge of ice sheet and glacier dynamics has matured to the point that we no longer consider such ice masses as having existed in an equilibrium state at any time. High frequency Dansgaard-Oeschger events, the analyses of Heinrich layers, Bond cycles, and abrupt climate events such as the Younger Dryas episode all bear on the complex relationships in the interactions between the ocean, atmosphere, and cryosphere systems at sub-Milankovitch time scales. As Broecker and Henderson (1998) remind us, we still do not fully understand the mechanisms that drive glacial to interglacial climate change. What process initiates the demise of glaciations? A growing wealth of evidence indicates that ice accumulated rapidly in the Northern Hemisphere during times of transition, *e.g.* at the Stage 11/10, 5e/5d and 5a/4 boundaries as described in the isotopic marine records; however, these transitions remain difficult to model and there is disagreement over where these ice masses were initially located. In fact, we still are without consensus as to what series of events lead to the first glaciation of the Northern Hemisphere and why cyclical glaciation became dominated by the 100 ka Milankovitch periodicity after being dominated by 41 ka forcings for at least 1.8 My.

**Recommended Research Foci**

The paleoenvironmental record provides a number of opportunities to improve our estimates of climate sensitivity, feedback mechanisms, and system response times. We now have a large array of extant paleoenvironmental information that needs to be synthesized (*e.g.*, CAPE, QUEEN, PONAM and other projects) as circumarctic reconstructions. Specific periods of altered climate forcing are already receiving significant attention. In each case, not only are circumarctic temperature reconstructions being addressed, but also more detailed information regarding key feedback processes. In each of the following we need more certain estimates of the distribution and character of past sea-ice, land ice and thermohaline circulation:

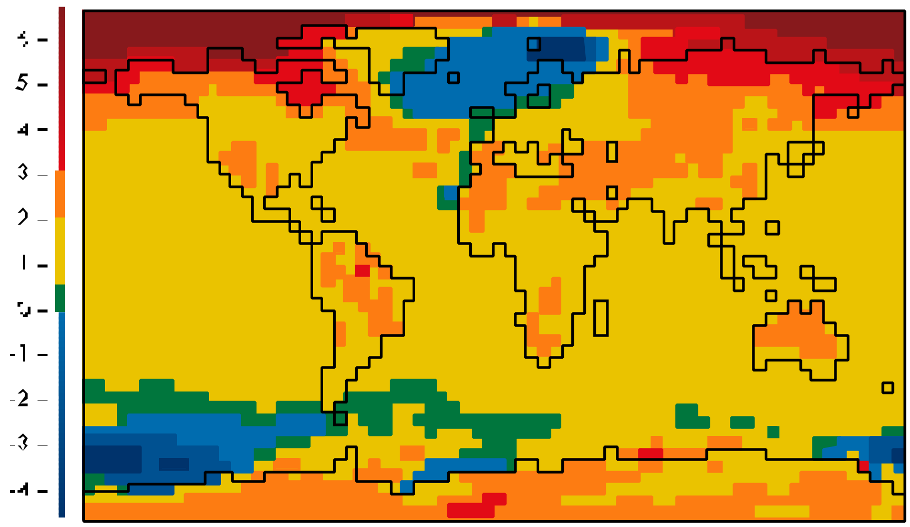
- the last 2000 years - varied climate that can be studied with quantitative reconstructions of both past climate change and forcing;

- the early to mid-Holocene - summers warmer than today;

- the Last Glacial Maximum - significantly colder than today;

- the last interglacial (MIS 5) - warmer than today, with sea level up to 6m higher than today (reflective of reduced ice sheet thickness/extent);

- MIS 11 - warmest of recent interglacials, also associated with highest sea levels (reduced ice sheets) in last 500,000 years;



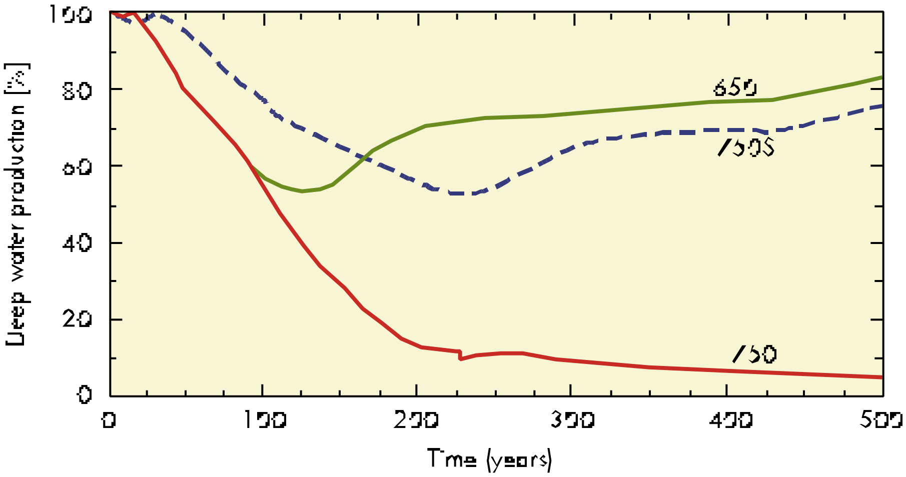

8. NASA-GISS IPCC coupled atmosphere-ocean model simulation of the possible change in surface air temperature (°C) by the middle of the 21st century compared to today (given IPCC95 greenhouse gas forcing). Note that this and other coupled runs suggest that changes in the thermohaline circulation could occur, and thus, that future warming will be non-uniform around the Arctic. Simulation available at: http://www.giss.nasa.gov/cgi-bin/co2hansen.cgi

- Ice-free Arctic (ca. 2-3Myr) - what climate change might lead to an ice-free Arctic in the future? How close now are we to an ice-free Arctic?

**What are the interrelationships between sea ice, arctic river runoff, and ocean circulation patterns?**

Recent coupled atmosphere-ocean modeling indicates that changes in high-latitude hydrologic balance could slow or alter the global system of thermohaline ocean circulation and dramatically alter the transport of heat by Atlantic currents (Figures 8, 9; Rahmstorf, 1997; Stocker and Schmittner, 1997, Stocker, 1998; Ganopolski *et al.*, 1998; Paillard, 1998). Realistic assessments of hydrologic and oceanic processes and their interactions are needed to determine how future changes in the Arctic could affect the global climate.

The Arctic Ocean and its epicontinental seas are the key areas for studying the relationship between sea ice and river runoff, their effect on oceanic salinity, and how these elements subsequently affect ocean circulation. Lying principally at depths of < 200 m, the shallow continental shelves bordering the Arctic Ocean comprise 25% of the world's total continental shelf area. Freshwater discharge from the large rivers flowing into the Arctic Ocean and adjacent seas from the circumarctic land masses provide approximately 10% of global runoff (Stein 1998) and a freshwater source for sea ice growth on the shallow continental shelves and the maintenance of the arctic halocline. the water budget of the modern arctic ocean is balanced by fresh water sources of about 30% from the Bering Strait and 60% from rivers (Figure 10; Aagaard and Carmack, 1989). Changes in this fresh-water balance

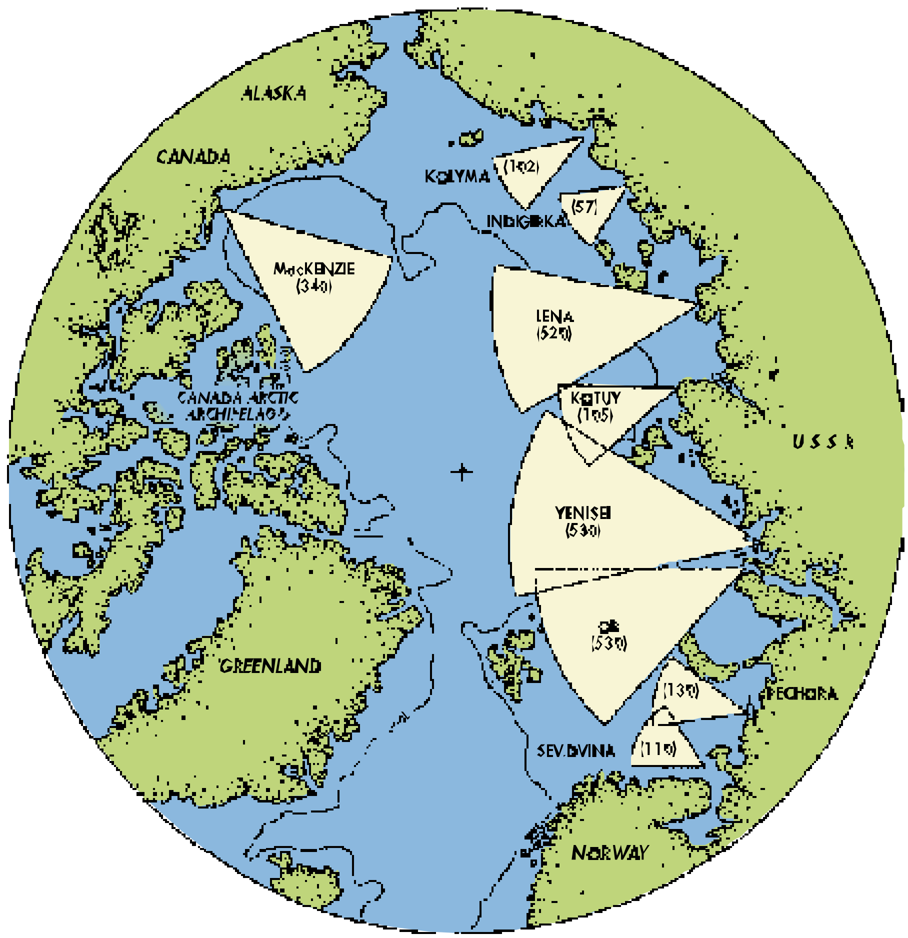



9. Evolution of the circulation in the North Atlantic for different climate scenarios: Curve "650" shows the evolution for a scenario in which the atmospheric concentration of greenhouse gases stabilizes at 650 ppmv on a $CO^2$ equivalent basis, given the present rate of concentration increase (1%/year). The circulation weakens, but then recovers to stabilize. If instead the atmospheric concentration of greenhouse gases stabilizes at 750 ppmv (Curve '750'), the ocean circulation breaks down completely and does not recover. However, if the concentration of greenhouse gases in the atmosphere were to grow at only half the present rate (0.5%/year) up to a level of 750 ppmv, the circulation weakens also, but the reduced rate of increase allows the circulation to recover (Curve '750S'; after Stocker and Schmittner, 1997).

would influence the extent of sea-ice cover. At present, sea ice covers the epicontinental shelves and deep ocean areas of the Arctic Basin for at least 10 months of the year limiting heat transfer from the ocean to the atmosphere and playing a significant role in planetary albedo.

After breakup, sea ice provides a source of relatively freshwater outflow from the Arctic to the Atlantic Ocean where it interacts with warm, saline North Atlantic waters (cf. Pfirman *et al.*, 1989; Aagaard *et al.*, 1985, 1991). The freshwater flux that leaves the Arctic Ocean is a strong control on ocean circulation, particularly on the formation of North Atlantic Deep Water (Figure 11; Rahmstorf, 1994). Marine productivity on arctic shelves is strongly influenced by sea ice thickness and distribution, flux of freshwater and related nutrients, and nutrient supply from the Bering Sea (Grebmeier *et al.*, 1995). These in turn have profound effects on fish stocks and marine mammal populations, and indigenous peoples.

The presence or absence of permanent ice in the Arctic Ocean has a major impact on the climate and vegetation of the adjacent continents. One of the long-standing debates in arctic research has been over the initiation and persistence of perennial sea ice across the Arctic Ocean. While the literature includes estimates putting perennial ice as far back as 5 My (Clark *et al.*, 1980, 1990), more recent work places permanent sea ice in the more recent past. The relatively warm paleoceanographic and atmospheric conditions that nurtured a forested Arctic as late as about 2.6 My ago in the mid Pliocene (Brigham-Grette and Carter, 1992) must have come to an abrupt end with the initial onset of major Northern Hemispheric glaciation at about the same time. What caused this shift? And what was the character of late Pliocene-early Pleistocene



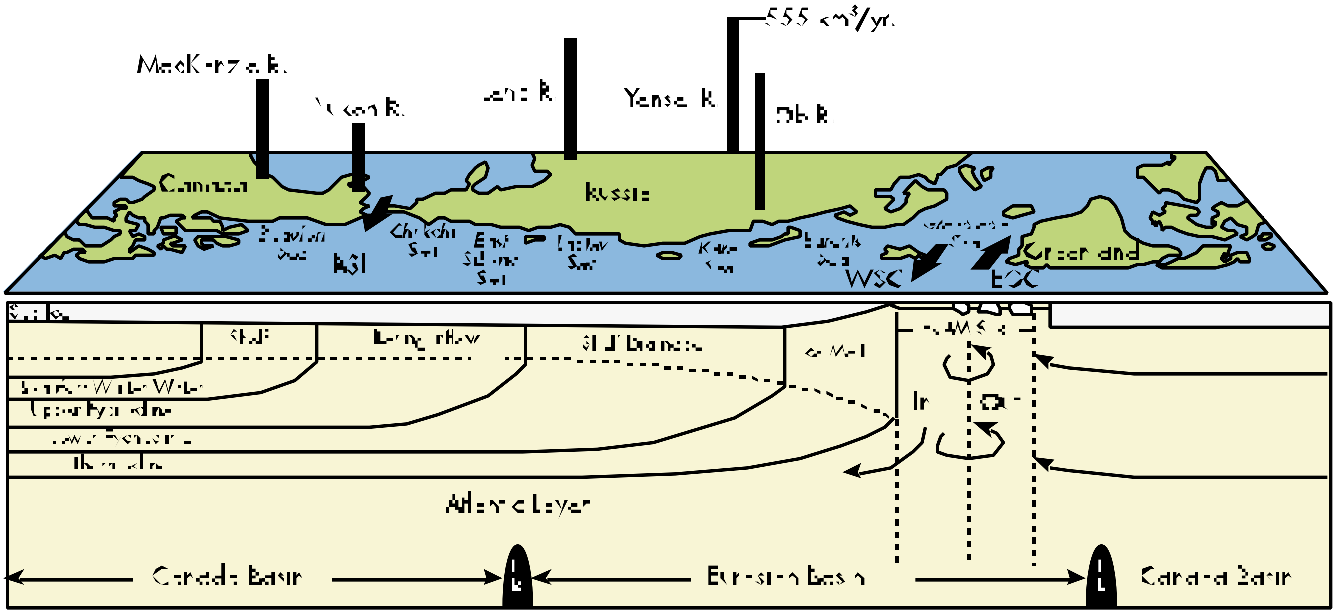

10. Mean annual runoff of the nine largest rivers to the Arctic Ocean in cubic kilometers per year (after Aagaard and Carmack, 1989).

glacial/interglacial climate given that after the first glaciation, subsequent warm events allowed for the return of forests to Northern Greenland and the possible demise of the Greenland Ice Sheet (Funder, *et al.*, 1985). While we vaguely understand the qualitative nature of these shifts, further observation and modeling studies will permit a more certain assessment of an ice-free Arctic Ocean and its implications for future global climate.

**Essential research (modified from RAISE, 1997)**

- Document historic variations in terrestrial water balance and fresh water discharge to the Arctic Ocean.

- Develop and evaluate proxy indicators of riverine water and dissolved and particulate matter input into the Arctic Ocean and




11. Schematic drawing of circulation and stratification patterns associated with river inflow and halocline ventilation in the Arctic Ocean (modified from Carmack, 1990). Shown is river runoff scaled to average annual discharge of 555 km³ of the Yenisei River (after Forman and Johnson, 1998).

the northern seas. Maintain and further develop databases and models of river discharge, sediment load, and geochemistry for arctic watersheds.

- Determine the formation, extent and variability of sea-ice cover on annual to millennial scales. Inquiry should consider entrainment and fate of biological and geochemical materials in the sea ice.

- Evaluate changes in sea level on the arctic shelves, including eustatic and isostatic factors, and resulting bathymetric evolution over the past 20,000 years. Information is needed on the co-evolution of river discharge foci, degradation of permafrost and changes in shelf currents with sea level variation.

- Obtain sediment cores from estuarine and shelf environments to understand past changes in sediment flux, river discharge and chemistry, sea-ice cover and sea level. Use biotic and geochemical indices to quantify changes in water mass structure, circulation, and the distribution of biologic communities.

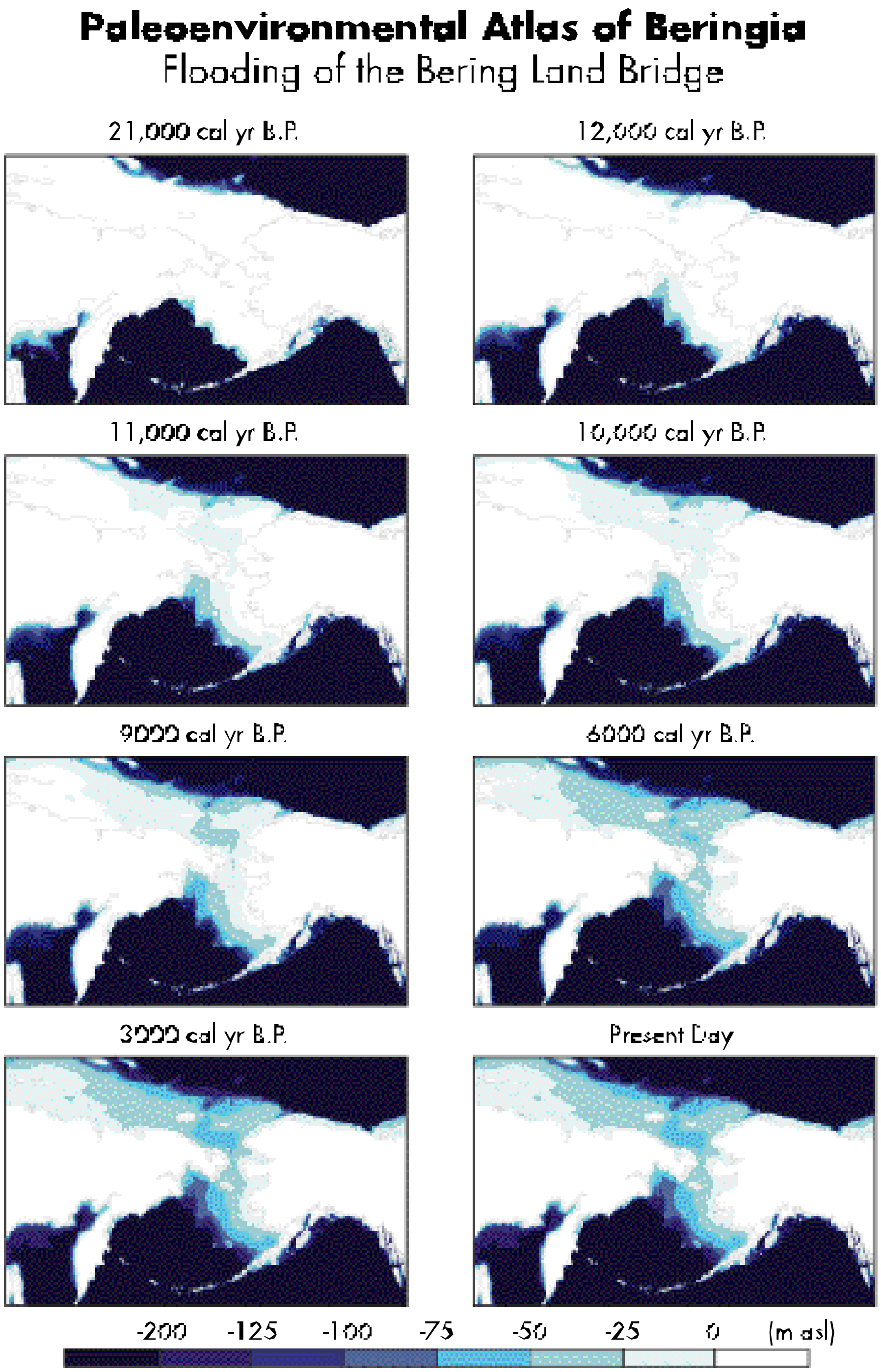
- Determine the linkages between changes in watershed-to-shelf transport processes and primary productivity. Evaluate the spatial and temporal variability of biological productivity in estuary, delta, and shelf environments. Inquiry should focus on the natural states of productivity and potential response to environmental change.

**How have changes in arctic albedo affected earth energy balance and climate?**

The distribution of arctic vegetation cover, glacial ice cover, permanent and seasonal sea ice and snow cover produce large geographic differences in arctic albedo. The generally high albedo of the Arctic is an important factor in the energy balance of the Earth and changes in vegetation, ice or snow conditions due to climactic changes can be important feedbacks promoting local to global climate change. Recent model experiments, for example, indicate that a northward movement of boreal forest in the continental portion of Arctic Canada could cause significant warming of global climate due to decreased arctic albedo (Foley *et al.*, 1994). In contrast, the replacement of forest vegetation by tundra may be important in radiative driving of the onset of arctic glaciation during glacial periods (Gallimore and Kutzbach, 1996). LANDSAT imagery, combined with field studies, indicates that large areas of the uplands of the eastern Canadian Arctic were mantled with a thin permanent snow/ice cover during the last 350 years, the Little Ice Age (Andrews *et al.*, 1976; Locke and Locke, 1977). This type of mapping provides the basis for energy balance modeling of the climate change and feedback mechanisms that would be required for ice sheet initiation (Williams, 1978).

**Essential Research**

Fossil pollen and plant macrofossil evidence from lake sediments, peats and other deposits can be used to reconstruct the distribution of arctic vegetation cover over a wide spectrum of time scales. Together with spatial information, such as past forest position and thaw-lake fields, we can improve our understanding of the role of albedo changes on climate. Large-scale syntheses of such data have been initiated, *e.g.*, Beringia (Figure 12) and for the entire Arctic for selected time slices. Significant gaps, however, still exist in the data availability for large segments of the Canadian and Russian Arctic. Efforts must be made to establish a geographically representative network of fossil pollen sites for the circumarctic and to reconstruct past ice extents in order to calculate reasonable estimates of overall albedo change through the Holocene.




12. Flooding of the Bering Land Bridge over the last 21,000 cal. years BP generated by applying the global eustatic sea-level curve (Bard *et al.* 1996) to modern bathymetry (GETECH 1995). The entire sequence can be viewed in an animated form at 1000-year intervals on the Beringian Atlas Home Page: (http://www.ngdc.noaa.gov/paleo/pale/atlas/beringia/index.html).

## Imperative Four

### Document the history and controlling mechanisms of biogeochemical cycling of nutrients and radiatively active species.

The Arctic stores large amounts of carbon in tundra soils. It is estimated that the Arctic and subarctic contain 25% of the global soil-carbon pool (Oechel and Vourlitis, 1994), and approximately 13 times the total amount of carbon in the atmosphere may be buried in the upper 100 meters of arctic permafrost. It is likely that peatlands dominate carbon soil sequestration in the Arctic and subarctic. Theoretical considerations, however, suggest that this reservoir may be delicately poised with respect to changes in temperature and the water balance. Carbon fluxes and the potential for carbon sequestration or release on annual to decadal time scales in arctic ecosystems is thought to be large enough to impact global atmospheric $CO_2$ concentrations (Semiletov, 1995; Oechel *et al.*, 1993). Similarly, processes of methane release or sequestration are sensitive to temperature and especially the water balance of arctic soils. Primarily because the growing season in the Arctic and subarctic is so brief, year-to-year variability in summer temperatures can have a dramatic effect on productivity and carbon storage. Small changes in the Arctic and subarctic thus can have large impacts on the global carbon cycle.

Direct observational records of greenhouse gas concentrations in the atmosphere extend, at most, 40 years into the past. Our understanding of greenhouse gas concentrations prior to this time period is derived from polar paleoenvironmental archives (Figure 2). Variability in $CO_2$, $CH_4$ and $N_2O$ over the past millennium on annual to near-annual time scales is largely unknown, yet we are increasingly aware that the modern cycles of these gases vary considerably, and we do not know if this variability is linked with human activities or if they are natural.

Information on the biogeochemical cycles of nutrients in the past is also lacking. The cause of global variation is uncertain, but it is likely that changes in the geochemical cycling of carbon in the Arctic played a significant role.

Transport mechanisms are central to Arctic biogeochemical cycling. Glaciers, rivers, and wind transport sediment and nutrients to the Arctic Ocean and adjacent seas, where they contribute to biological productivity and, among other effects, influence sea-ice albedo. Many processes of sediment generation and transport are unique to the Arctic. Of special interest is the recent observation that wet-based glaciation greatly increases sediment production compared to nonglacial environments, often by 1-2 orders of magnitude (Hallet *et al.*, 1996). The switch to cold-based glaciation, however, can reduce sediment production to an even greater extent. The large changes in nature and extent of glaciers, permafrost, and other arctic elements over the last glacial cycle, and the expected large changes in the future, will certainly impact nutrient and sediment cycling in fundamental ways.

Arctic archives can play a much larger role in defining the natural variability in these cycles and how they behaved prior to the human intervention of the past century. Although the effects of human-created contamination have begun to be felt in the Arctic, the region is still largely untouched in a direct sense by human activities, and thus is a valuable recorder of anthropogenic impacts on both the regional and global scale. The Arctic is a fragile region that deserves our continued attention.

The study of peatlands is an example of a paleoenvironmental approach to understanding arctic biogeochemical cycles. Radiocarbon dated cores from the extensive northern peatlands of Arctic North America and Eurasia can be used to determine when these vast stores of carbon began to develop and how such development might be tied to Holocene climactic changes (Zoltai and Vitt, 1990; Korhola *et al.*, 1995). The study of these cores can provide bulk density estimates of peat-carbon content and analysis of peat decomposition can provide evidence of how rates of carbon sequestration and methane generation has changed over the Holocene in response to climactic variations (Gorham, 1991; Korhola *et al.*, 1995). At present, such studies remain geographically scattered, particularly in the Russian Arctic (Botch *et al.*, 1995). A first step in defining biogeochemical cycles is to collate existing data on peat depth, accumulation history, and carbon content and sequestration rates from arctic regions. Areas where such information is sparse should be identified and cores taken to provide the above information. Appropriate scaling techniques to extrapolate from core points to landscapes and regions of peatlands should be developed in tandem. The most promising approaches will likely be based upon remote sensing and geographic information systems. Actively eroding thaw lakes incorporate terrestrial carbon from the surrounding landscape, some of which is probably metabolized and released as $CO_2$ during the open-water season. Lake sediments are similarly a significant sink and potential source of carbon in arctic environments that could be studied in a similar manner.

Questions

- How can we reconstruct terrestrial nutrient flux in the past?

- How have changes in glaciers, permafrost, and other land-surface elements affected nutrient and sediment fluxes?

- Has the residence time of carbon in tundra soils changed over the last 10,000 years?

- What is the history of $CO_2$ over the last 10,000 years and, in particular, over the last 1000 years?

- Similarly, what is the history of methane and $N_2O$ over the Holocene?

- Can we reconstruct the history of water vapor in paleoenvironmental archives from the Arctic?

- What is the role of the Arctic in the methane cycle?

- How much of a role does the Arctic Ocean play in biogeochemical cycles?

- What are the mechanisms by which ice cores record the gaseous composition of the atmosphere?

**Recommended research and needs**

- Numerous well-dated, high-resolution records of atmospheric composition over the Holocene are needed. Despite their obvious importance in establishing pre-industrial behavior of key biogeochemical cycles, such records are lacking.

- Process studies of nutrient and sediment fluxes in arctic environments, with special focus on glaciers.

- Recovery of radiocarbon-dated cores from extensive northern peatlands of Arctic North America and Eurasia to determine when carbon storage began and subsequent rates of sequestration.

- Collation of global datasets on peat depth, accumulation history, carbon content, and carbon sequestration rates.

- Development of proxies for nutrient fluxes into and out of arctic ecosystems. Information on past nutrient fluxes is essentially non-existent, yet nutrient availability is important, for example, in determining carbon photosynthetic and respiratory fluxes.

- Obtain a better understanding of how ice cores record the concentration of atmospheric gases, particularly those greenhouse gases that affect the Earth's energy budget and climate.

- Exploit isotopic techniques to determine potential sources and sinks of methane during the Holocene and last glacial.

- Obtain information on the timing and rates of thaw lake development during the Holocene and contemporary gas fluxes between thaw lakes and the atmosphere.

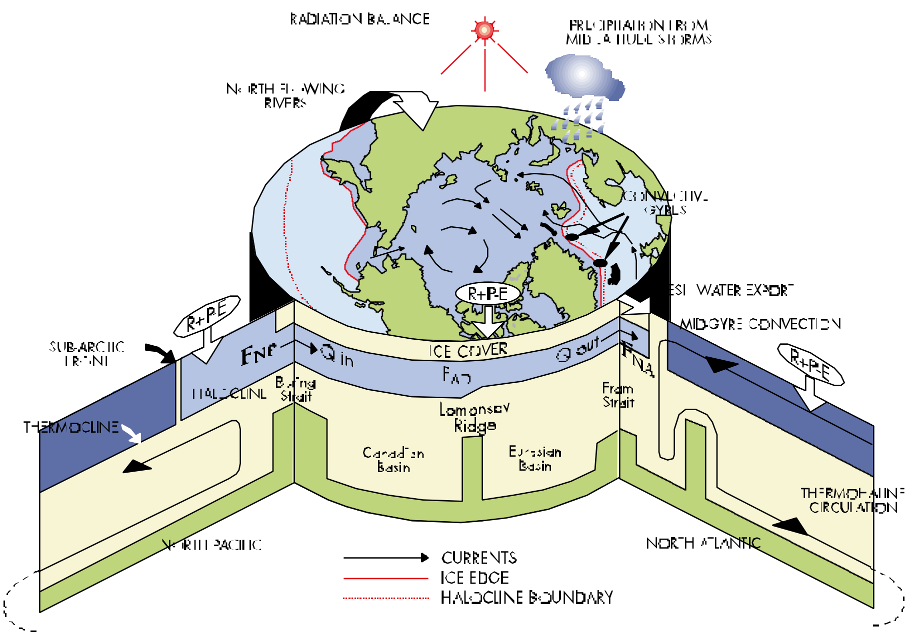
## Imperative Five

**Evaluate the realism of state-of-the-art numerical models being used to predict future climate and environmental change on regional to global scales.**

A goal of the U.S. Global Change Program is to use quantitative models of the earth system to predict future global changes and their regional environmental, ecosystem and socio-economic implications. Both global models, which couple components for the atmosphere, ocean, cryosphere, and biosphere (*e.g.*, Washington and Meehl, 1996; Manabe and Stouffer, 1994), and regional models, which include resolution fine enough to predict climate processes such as precipitation and storm patterns that depend on detailed topography and coastlines (*e.g.*, Giorgi, 1995; McGregor, 1997), have been applied to this task. Validation of the predictive capability of these models for future climates requires demonstration that they can simulate natural climates different than the present. The paleoclimate proxy record provides the database for evaluating these climate models and understanding the nature of interactions among the *spheres* of the earth system and altered forcing.

**Can models reproduce the arctic temperature record on both temporal and spatial scales for ca. 400 years from reconstructed forcings of solar irradiance, volcanic inputs, and greenhouse gases?**
The instrumental record of climate observations is too short to describe the full range and nature of climate variability in the Arctic, and, additionally, has been affected by anthropogenic activity. It is inadequate for understanding the coupled earth system and its response to different climate forcing factors. The paleoclimate proxy record, however, provides a much longer test bed. The paleoclimate proxy record from lake sediments, trees, glaciers, and marine sediments establishes a warming in the Arctic of ~1.5°C during the mid-19th to 20th centuries (Figure 4; Overpeck *et al.*, 1997). This warming ended a period of colder temperature, the "Little Ice Age," which began before AD 1600. Anthropogenic increases in the greenhouse gases can explain only a portion of this warming. Changes in solar irradiance (Lean *et al.*, 1995) and volcanic activity (Zielinski *et al.*, 1994) have been proposed as forcing mechanisms (Figure 1) to explain the remaining variability.

Climate models are needed to test the efficiency and timing of these proposed mechanisms in forcing climate variability reconstructed for the Arctic. These models, which have been shown to reasonably simulate features of the present-day circumarctic, such as sea ice extent (Weatherly *et al.*, 1998) and the North Atlantic Oscillation, can provide an understanding of the interactions and feedbacks between altered forcing and Arctic climate variability. In particular, insight into the

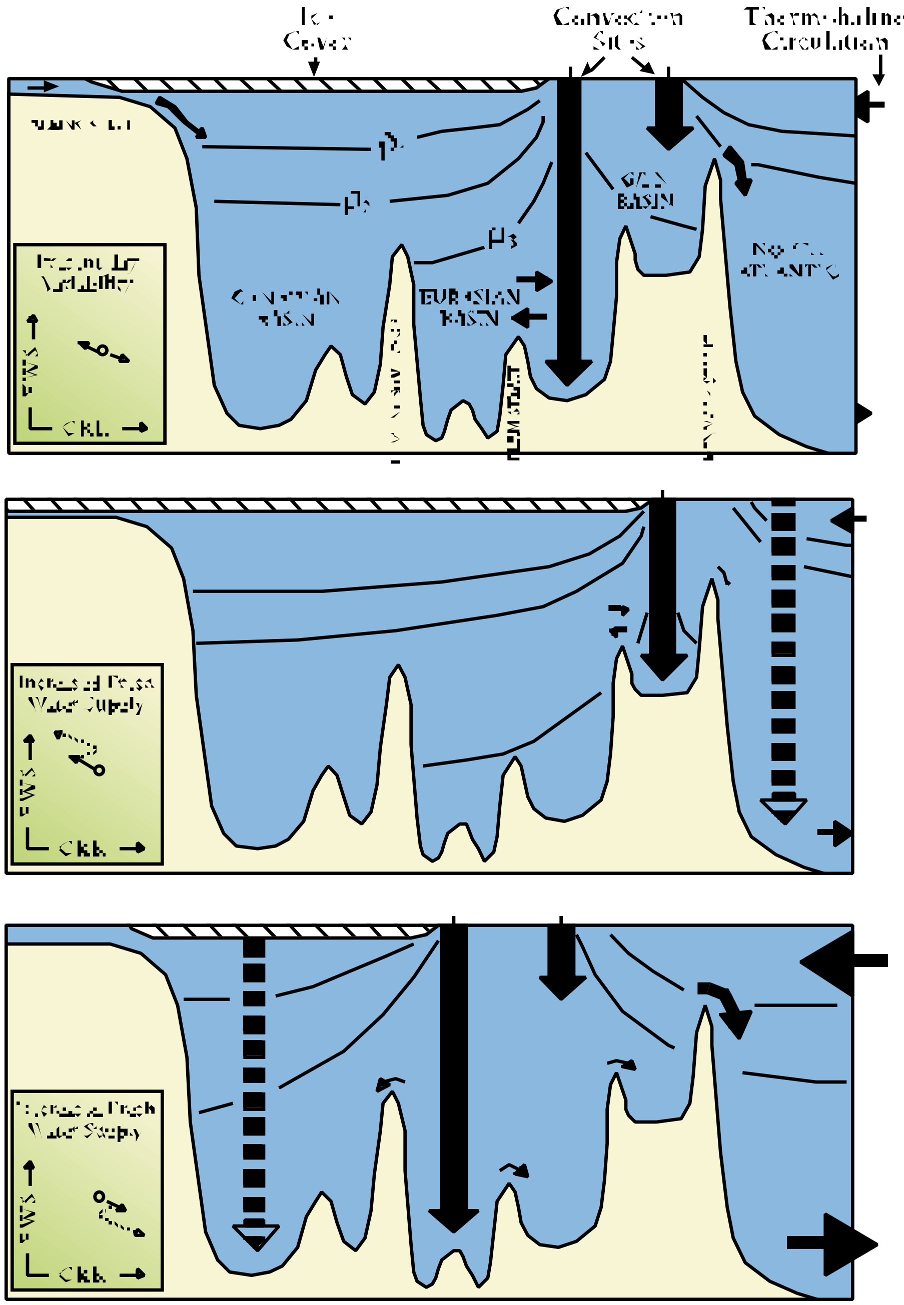



13. Schematic Arctic Ocean – Climate connections. In the horizontal plane, the extent of sea ice in winter is shown by the shaded region and the mean surface circulation by arrows. Sections from the North Pacific and the North Atlantic extend through the Bering and Fram Straits, respectively. The subarctic front separates the salt-stratified upper waters of the arctic and subarctic oceans from the temperature-stratified upper waters of the subtropical oceans. The components of fresh water balance include runoff (R), precipitation (P), evaporation (E), storage in the upper North Pacific (FNP), the Arctic (FAO), and the North Atlantic (FNA), and the horizontal freshwater fluxes (Qin and Qout). Shaded ovals indicate the present sites of convection in the Greenland and Iceland Seas (after Aagaard and Carmack, 1994).

following questions may be gained: What are the roles of internal (*e.g.*, coupled atmosphere-ocean-sea ice processes) and external processes? Have the major recognized climate phenomena such as NAO, PNA, AO, ENSO and their interactions with the Arctic changed over this time period? How are past climactic events (*e.g.*, “Little Ice Age,” “Medieval Warm Period”) recorded across the Arctic?

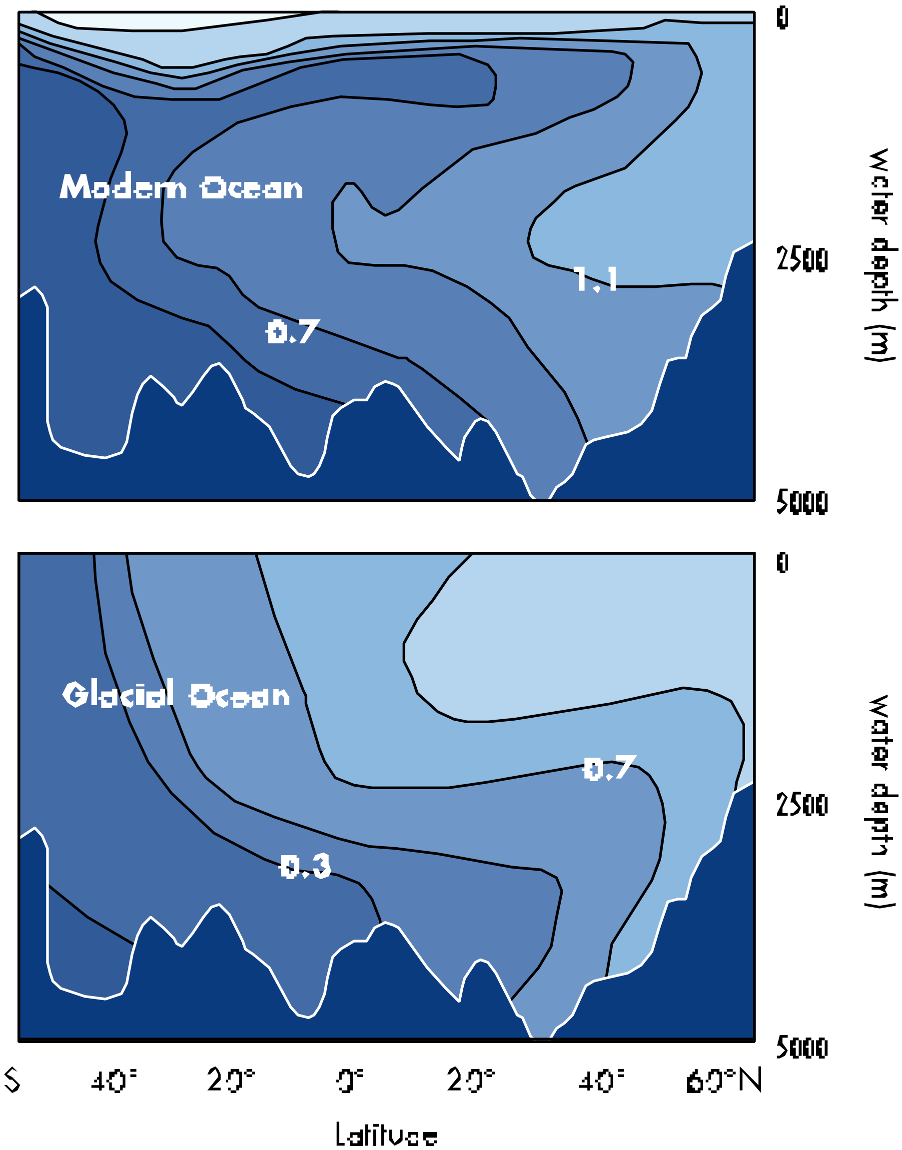
**Can models reproduce the known paleoceanographic changes in the thermohaline circulation in the North Atlantic over the past 20,000 years, with inferred ice sheet and sea ice extent and fresh water inputs? How does the concomitant model-derived climate compare with proxy terrestrial records?**

The Arctic Ocean exerts a strong influence over the large-scale thermohaline circulation of the ocean through the rate of outflow of fresh water in the East Greenland Current (Figure 13; Aagaard and Carmack, 1994). The large-scale overturning cell in the world ocean is driven largely by the convection in the Greenland, Iceland, and Norwegian Seas. The strength and location of the convection in these subarctic seas is conditioned by freshwater export from the Arctic Ocean via the East Greenland Current (Aagaard and Carmack, 1994). Different climates appear to be associated with different modes of the convection. Vigorous thermohaline circulation, driven by convection cells in the high latitudes, corresponds to moderate European climate, as warm as today or warmer. Weakened convection, and/or convection displaced to



14. Hypothesized dependence of the convective renewal rate (CRR) on freshwater supply (FWS) from the Arctic Ocean under (a) present conditions, (b) increased freshwater supply, and (c) decreased supply. The size of the arrows through the right-hand side is representative of the strength of the thermohaline circulation forced from the far northern seas. The barred arrows represent the extreme locations of convection. The solid arrows in the insets indicate the trend in convective renewal with changing freshwater supply, and the dashed arrows indicate possible transitions to different circulation modes (after Aagaard and Carmack, 1994).

the south, corresponds to dramatically reduced thermohaline circulation (Figure 14) which is thought to be associated with much colder glacial maximum and Younger Dryas paleoclimates when the sea ice cover expanded southward (Figure 15). A modern example of the importance of freshwater disturbances to the thermohaline circulation is the Great Salinity Anomaly, an event initiated by a larger than normal discharge of sea ice from the Arctic Ocean which resulted in cooling and freshening of the North Atlantic Deep Water (Dickenson *et al.*, 1988).




15. Latitudinal distribution of del$^{13}$C (per mil) versus depth for the modern and glacial Atlantic Ocean. The modern measurements were made on water samples, whereas the paleoceanographic reconstruction is based on the isotopic composition of benthic foraminifera that lived at the sediment-water interface. Rates of North Atlantic Deep Water (NADW) formation varied dramatically during the last glacial-interglacial cycle, and were significantly reduced during much of the last glacial period (after Labeyrie *et al.*, 1992; Overpeck and Duplessy, 1994).

Model simulations have been used to study the multiple modes of thermohaline circulation and quantify the rapidity of changes between these states under various forcing factors (Rahmstorf, 1994; Stocker *et al.*, 1992; Manabe and Stouffer, 1988). Continued collaboration between modelers and the paleoclimatologists documenting the past behavior of the thermohaline circulation will result in improved understanding of the causes of rapid change and the improved prediction of future behavior of the thermohaline circulation.

**What is the climate sensitivity during the Holocene to changes in arctic albedo associated with sea ice, sea level, and vegetation variability?**

Future anthropogenic climate change resulting from increasing greenhouse gases and sulfate aerosols will lead to surficial changes in vegetation, sea ice, and sea level in the Arctic. These variables have also changed throughout the Holocene in response to climate change resulting from ablation of the ice sheets, increasing $CO_2$, and varying orbital insolation. General circulation models (GCMs) enable us to determine the sensitivity of the climate system to these changes. Vegetation, sea ice, and sea level impact the Arctic climate largely through the albedo feedback effect. Global warming may lead to an expansion of the treeline to the north (Foley *et al.*, 1994) and decreased sea ice which are both positive feedbacks to global warming. Global warming will lead to rising sea levels; sea levels also rose during the Holocene due to the melting ice sheets. Since the magnitude of such changes throughout the Holocene (and as predicted for the future) is small relative to the resolution of global GCMs, regional climate models (RCMs) may be used to ascertain these climate sensitivities during the Holocene. These sensitivity studies will enable us to understand the importance of these boundary conditions on Holocene climates, as well as their potential impact on the arctic climate in the future.

**Is model response to altered forcing (*e.g.* ice sheet extent, albedo, insolation) consistent with proxy evidence of the past changes in hydrology?**

Dramatic changes in the hydrology of the Arctic occurred during the past 20 ka. In particular, discharge of many Eurasian rivers was probably reduced during the last glacial maximum, reflecting colder and dryer climates of the Siberian lowlands. Advancing glaciers, with significant storage of water in proglacial lakes, and blockage of river flow diverted some drainage. Thus, during the last glacial maximum, freshwater discharge from arctic rivers into the Arctic Ocean may have been dramatically reduced, affecting sea-ice production, sediment and nutrient fluxes, halocline structure and thermohaline circulation. The deglacial rise in sea level and glacier retreat may have led to a rapid increase in freshwater input into shelf sea, heralded by depleted $^{18}O$ values in planktonic foraminifera from the Arctic Ocean (Stein *et al.*, 1994). Full rise in sea level by the middle Holocene, coupled with northern expansion of treeline and concomitant degradation of permafrost, also may have increased fresh water and nutrient input into northern oceans. Refined earth system models are needed that provide a realistic footprint of the last ice sheet and associated changes in drainage systems, particularly in Eurasia. These models should integrate changes in land cover and sea and sea-ice area during the last deglaciation to better evaluate climate forcings intrinsic to the Arctic (*e.g.* Ganopolski *et al.*, 1998)

Questions remain on decadal to millennial variability of four of the ten largest rivers in the world that drain onto the arctic continental shelves (Figure 10): the Yenisei (603 $km^3$/yr), the Ob (530 $km^3$/yr), the Lena (520 $km^3$/yr), and the MacKenzie (340 $km^3$/yr). Changes in riverine input into the Arctic Ocean margin would influence sea-ice formation and transport, productivity, lateral ventilation of the Arctic Intermediate Water and exchange of Arctic, Atlantic and Pacific waters. Knowledge is needed on how arctic riverine discharge, reflected in the sea ice system, effects thermohaline circulation and initiates "great salinity anomalies" (Figure 6; Belkin *et al.*, 1998).

**How are hemispheric-scale changes in climate expressed at the regional to local scale and how do responses at these scales in turn feed back to the climate system?**

Global and hemispheric changes translate into regional climactic phenomena due to the response of the climate system itself and the influence of regional geography. Thus responses are not necessarily predictable and may be of opposite sign in adjacent regions. In turn, feedback from the earth surface to the climate system occurs at the regional and local scale, so an understanding of the way the smaller-scale climate patterns and responses are generated is essential to accurate predictions of future conditions. An understanding at this level of detail requires a nested hierarchy of models, with realistic representations of land-atmosphere/ocean-atmosphere interactions.

**How well can we model climate-induced changes in lacustrine, fluvial, eolian, glacial, periglacial, ecological and other systems that may be impacted by climate change in the future?**

Future climate change may be large enough to have significant impacts on the environmental features of the Arctic. Although models for many of these systems may already exist, their ability to simulate the response of a given system (*e.g.*, lacustrine, eolian, glacial, periglacial or ecological) to climate change has been limited by the lack of detailed data on climate-induced changes of the past. Some data of this type has been generated, but efforts need to be made to develop a rigorous paleoenvironmental framework for testing climate change impact models. This work will have the added benefit of enhancing our ability to simulate environmental processes that can, in turn, impact climate or biogeochemical change.

**Recommended research and needs**

- Time series of updated forcings for ca. 400+ years of solar irradiance, volcanic input, and greenhouse gases.

- Coupled climate model simulations for the time period AD 1600 to modern, testing individually and in combination the roles of internal feedbacks and forcing of solar irradiance, volcanism, and greenhouse gases on the climate of the Arctic.

- Data of freshwater inputs (magnitude, duration, and location) for important periods (*e.g.*, 8.2 ka, Younger Dryas) over the last 20 ka.

- Coupled climate simulations to understand the thermohaline circulation and its impact on the Arctic climate during the Last Glacial Maximum, Younger Dryas, and periods of freshwater inputs (*e.g.*, Heinrich events and Dansgaard-Oeschger cycles).

- Regional climate model simulations of changing vegetation and sea level corresponding to conditions from the early Holocene to present.

- Sea ice reconstructions and proxy development for the hydrologic cycle including precipitation, evapotranspiration, and river discharge.

- Experiments with uncoupled and coupled climate models to test the sensitivity of the Arctic climate to sea ice extent and duration during the Holocene.

## CROSS-CUTTING RECOMMENDATIONS

Each imperative has identified research recommendations and needs specific to its objectives and central scientific issues. As a scientific community focused on the Arctic's environmental history, we here outline the immediate research challenges and needs that crosscut the imperatives and will advance the science across a broad front over the next 3 to 5 years.

- Develop new or improve currently-used proxies that document past conditions, with particular emphasis on sea ice extent and duration, the hydrological cycle, and atmospheric composition. Encourage rigorous proxy calibration and modern process studies.

- Success of the overall PARCS effort will depend to a considerable degree on the establishment of a rigorous chronstratigraphic framework. It is essential that dating control and age calibration of records from diverse depositional environments be improved for the correlation of multiproxy records throughout the Arctic. To this end, ready access to AMS-$C^{14}$ must be provided.

- Improve or create networks of high quality marine or terrestrial records of various temporal resolution from key regions, specifically the northern North Atlantic, northern areas of the Russian Federation, Greenland, northeastern Canada and the Canadian archipelago.

- Examine possible mechanisms responsible for observed abrupt climactic changes on all time scales, glacial and interglacial.

- Improve understanding of arctic carbon and water cycle dynamics during the late Quaternary.

- Where appropriate, special attention needs to be focused on the influence of human activity on the environment, and the relationship of society and climate change.

- Develop forward and process models on regional to global scales and at key times (*e.g.*, the last 400 years, the mid-Holocene, periods of abrupt change including the last deglaciation, and the last interglacial).

# COORDINATED PROGRAMS: NATIONAL AND INTERNATIONAL

The paleosciences provide the temporal framework within which process-oriented programs study the modern arctic environment. PARCS will cross disciplinary lines and, for maximum effectiveness, needs to be closely integrated with many other elements of arctic global change research.

At the national level, close linkages with the components of the ARCSS and ESH Programs have worked well and will be strengthened through continued scientist-to-scientist interaction. As global change programs, ARCSS and ESH support a full spectrum of large, integrated, multidisciplinary research projects that are developed by the research community through workshops and steering committee activities. The system science approach requires an extraordinary amount of planning and cooperation among scientists from diverse disciplines. Research activities are often coordinated from the initial planning stages through implementation. A central tenet of the arctic paleoscience community is the timely sharing of data and results with colleagues in the wider scientific community.

The goal of the ARCSS Program is to synthesize ideas and integrate efforts that will lead to a holistic understanding of the arctic system within the context of the global environmental system. To this end, PARCS constitutes one of the essential components of the ARCSS Program. A key theme for ARCSS is the importance of land-ocean interactions and the variation in freshwater and chemical fluxes within the total arctic system. The history and consequences of these interactions is an essential objective of PARCS. PARCS will also provide the historical perspective for hydrological processes. A new, targeted, initiative within ARCSS is the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE) whose objective is to study "…dynamics of the coupled Arctic land-shelf system in response to external forcing and internal variability on a series of temporal and spatial scales." RAISE (Forman and Johnson, eds. 1998) constitutes a regional subset of ARCSS and includes many of the key paleoenvironmental elements identified in this report. As land-shelf interactions and sea ice dynamics are explored, linkage with RAISE, and other specific ARCSS components, will be strengthened, *e.g.* OAII. Also, links to LAII and SIMS projects will be developed, particularly through the application of regional climate models that examine land surface and climate interactions.

Proxy-calibration research on the current range of arctic climate variability and processes, and its synoptic-scale controls provides essential information for PARCS and all other components of the ARCSS Program. For proxy-calibration and "deep time" studies, PARCS will interact closely with the Arctic Natural Science (ANS) Program of the Office of Polar Programs (NRC/PRB, 1998). The ANS programmatic mission covers the entire spectrum of natural environmental phenomena in the Arctic, including glacial dynamics and permafrost. The ANS Program will be an important partner to advance the study of arctic modern processes (for proxy-calibration) and the paleosciences.

Maximum efficiency of the PARCS effort will be ensured by proactive interaction and coordination of the US community with other national and international projects that share common elements. Further, international cooperation is essential for the successful deployment of several projects because the research is undertaken in foreign lands or national marine waters. Several nations have territory within the Arctic (Russia, Finland, Sweden, Norway, Iceland, Greenland/Denmark, Canada, and the USA); and there are other nations who have developed active environmental research programs in the Arctic (*e.g.* Germany, The Netherlands, and the United Kingdom). Thus any program developed by a single country must be aware of the research agendas of other nations and coordinate within these larger international research efforts. International collaboration is an essential element in arctic environmental research; no single nation can support all of the research required. Within the U.S., arctic paleo-scientists should be aware of parallel or intersecting research efforts. To this end, PARCS will work closely with the Polar Research Board (PRB) of the National Academy of Sciences (NAS) to make paleoscience research in the Arctic more productive and responsive to the needs of the US and to aid in the PRB's interactions with the international community.

Over the past decades, PALE and GISP2 have led the way in establishing international collaborations. The relationship between US and European scientists during ice coring at the Greenland Summit was exemplary, and the extent of scientific and logistic cooperation was remarkable. From its initiation, PALE has sought collaborative links with researchers around the Arctic. PALE research objectives have been incorporated into the science priorities of Russia and Iceland, and PALE has collaborated with Canadian researchers through individual projects as well as national-level programs such as PACT. Ties to Norway and Russia are established through PECHORA, and to the European arctic research community through QUEEN. Where appropriate, these ties will be strengthened and new ones will be established.

The overarching paleoscience program at the international level is Past Global Changes (PAGES), an IGBP Core Project. It is clear that a strong relationship will develop between the newly established PARCS and the PAGES/IGBP effort. PAGES has developed research protocols that are utilized in several sections of this report, such as the identification of "Time Streams" and data coordination activities (IGBP, 1992). IGBP/PAGES Report No. 45 (1998) lists all of the presently active polar projects, several of which have bearing on the research agenda outlined in this report. PAGES has also published the research protocols (PAGES, 1994) designed by the PALE community to ensure consistency in the treatment of paleoenvironmental field sampling and analysis.

Within the PAGES organizational framework, the mission of Circum-Arctic Paleo-Environments (CAPE) includes much of what is outlined for PARCS. CAPE is an ongoing organization that has held several meetings and workshops at which the USA has been represented. PARCS may be considered the U.S. contribution to the CAPE effort. The primary emphasis of CAPE is to facilitate scientific integration of paleoenvironmental research on terrestrial environments and adjacent continental margins covering the last 250,000 years of Earth history. CAPE serves primarily to promote hemispheric syntheses, enhance data compilation and integration with ongoing related programs. Particular emphasis is given to the synthesis of circum-polar paleoenvironmental reconstructions over PAGES Time Streams I and II: annual records for the last 2000 years, and decadal to century-scale resolution over the last 250,000 years. The science objectives/questions of the CAPE project are:

1. What are the timing, rates, magnitudes, spatial patterns and controls of arctic climate variability?

2. What are the climactic controls over continental ice sheet inception, mass balance variation and recession?

3. What is the linkage and impact of the arctic climate system on the global system?

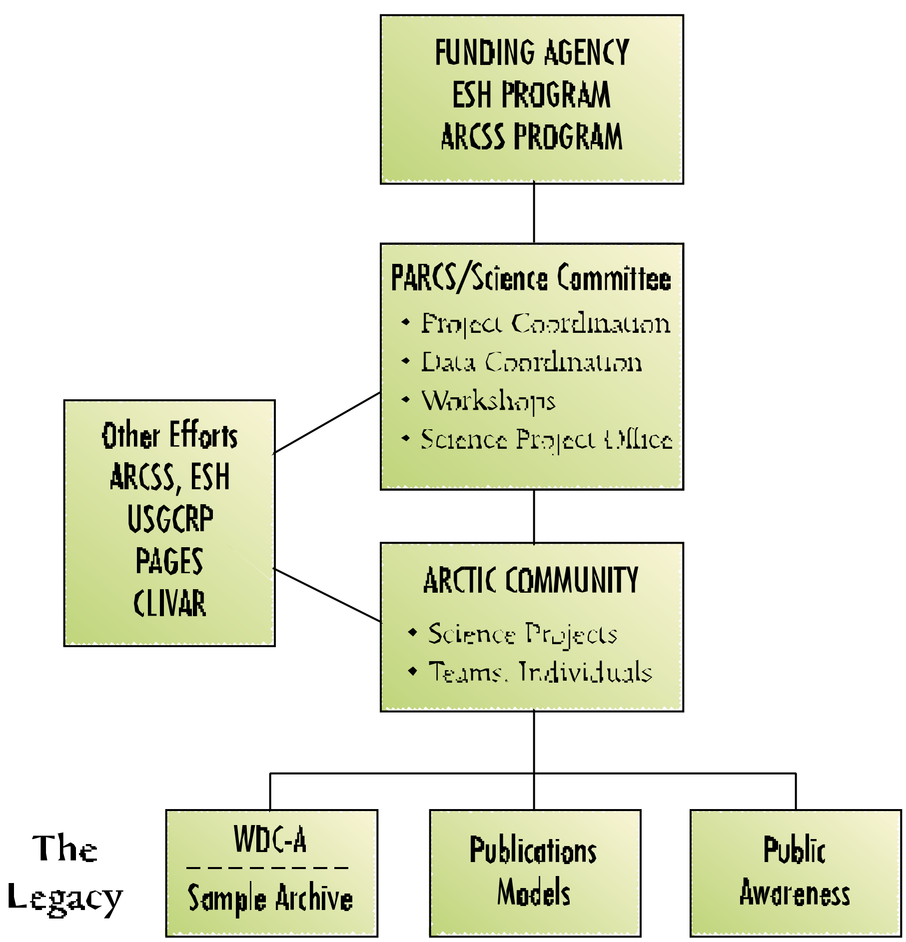
The CAPE effort serves as an effective linkage for the Pole-Equator-Pole (PEP) Transects (PAGES) at the northern high latitudes. The PEP Transects include the International Marine Past Global Changes (IMAGES) Project, also a PAGES initiative. The thrust of this effort is the recovery of long marine cores from sites of high rates of sediment accumulation and to focus on correlation of land-ocean records. In 1999 a research cruise to the Nordic Seas is planned; several core sites lie within the territorial waters of Arctic nations. Another PAGES program of interest is the Nansen Arctic Drilling (NAD) Program. Although the major focus is on time scales beyond PARCS, the project has the potential for providing long, high-resolution records from sites of mutual interest.

In this report, our emphasis is on the generation of time series with annual to century resolution. This requires the establishment of strong ties with the CLIVAR/WCRP Program (WCRP, 1998). One of the major goals of the arctic paleoscience community is the generation of high-resolution multiproxy records from tree rings, lake sediments, ice cores, and marine sediments. Comparison of these records in both the spatial and temporal domains will add a critical perspective to our understanding of seasonal-to-annual climate variability, which is currently limited to only the last 50-100 years - the general length of our instrumental records. Cooperation with the ACSYS/WCRP Program will also be essential in expanding our understanding of hydrologic and sea ice climatological processes in the Arctic.

# PARCS MANAGEMENT PLAN

## Administrative Structure

The PARCS administrative structure (Figure 16) will be simple and flexible, and encourage maximum input from the science community. This will allow community energies to focus on the actual research effort. PARCS will have the same status in ARCSS as the two process oriented programs — LAII and OIAA, and the newly developed RAISE and HARC initiatives. Each ARCSS Program component is guided by a steering committee (SC) which acts as a conduit for developing new initiatives and includes a science project office working with the PARCS/SC to coordinate community planning and project implementation. The membership of the PARCS/SC consists of funded investigators and others in relevant areas of research. The responsibilities of the science steering committee are:




16. PARCS Organizational structure.

- Advising the community on the objectives of the PARCS project;

- Identifying gaps in the scientific program and recommending new research directions;

- Suggesting and preparing input for the ARCSS and ESH science plans;

- Assisting in implementing and coordinating projects at the national and international levels.

The currently operating paleoscience component of ARCSS is PALE. The PALE Steering Committee will become the initial vehicle for the transition to a PARCS Steering Committee. The PARCS/SC would include representatives of the PALE community and it will be reformulated in terms of interest by the addition of researchers who represent the essential PARCS research sectors, such as: arctic ice coring, marine sediments, tree ring, and ice sheet/sea level communities. An initial *ad hoc* committee chaired by the PALE co-chairs would be charged with developing the necessary details of the new PARCS/SC.

The ARCSS Committee provides the overarching direction for the ARCSS Program and fosters the integration and coordination of all aspects of the effort. The ARCSS Committee is designed to contribute perspectives of the component steering committees as well as expertise from the wider research community. In a similar fashion, the ESH Steering Committee provides the overarching direction to the ESH Program. The Arctic paleoscience community will be represented on both of these committees.

## Data Management

### Background

At the earliest stages of PAGES planning, it was clear that a strong paleoenvironmental data management effort would be key for the success of PAGES. Many data needed by PAGES already existed and had to be made available in a useful form, and it was also clear that PAGES efforts would result in a rich legacy of new paleoenvironmental data and information. It was in response to this early need, that the World Data Center-A (WDC-A) for Paleoclimatology was established in 1992, and formally designated as the PAGES Data Coordination Center in 1993. Thus, PAGES included a strong and active commitment to data management from the onset of the project.

Since 1992, a great deal of progress has been made as the PAGES International Paleo-Data System became fully implemented. The current

PAGES International Paleo-Data System has benefited from input provided by hundreds of scientists from dozens of countries. Dozens of regional, national, and topical database efforts from around the world are now coordinated, including many of the projects conducted by the arctic paleoscience community. Public-domain data from over 7000 sites around the globe are easily accessible, along with many observed and simulated (*e.g.*, by 3-D climate models) regional to global arrays of data. Both raw data and information derived from the raw data are included, and all of the data are available over the Internet (http://www.ngdc.noaa.gov/paleo/paleo.html), as well as on a range of magnetic media.

**Data Policy – PARCS**

Given the PAGES experience, it is evident that careful archiving of data and its open dissemination to the broader scientific and educational community will be an essential measure of the long-term success of the PARCS effort. The current data archive of the arctic paleoscience community (PALE, GISP2) has grown considerably over the last decade and is now integrated into the paleo-data framework of the WDC-A for Paleoclimatology. It is critical to the success of the PARCS enterprise that the large amount of high-quality data collected by arctic paleoscience researchers continue to be effectively archived and made readily available to the broad scientific community.

**PARCS will adhere to the Data Policy of the Earth System History Program (ESH, 1995)**

"Successful global change research requires a strong commitment to the establishment, description and accessibility of high-quality data sets. Thus all data generated or used in ESH research will be shared in a full and open manner in accordance with USGCRP policy. ESH data should be submitted to the World Data Center-A (WDC-A) for Paleoclimatology (Boulder, CO) within three years of generation or at the time of publication, whichever comes first. The WDC-A provides advice on how to submit data to their permanent archives, and will make all paleoenvironmental data easily available via electronic and magnetic media."

**Data Coordination - PARCS**

The PARCS data effort must integrate seamlessly with the PAGES/WDC-A and ARCSS efforts. It is here recommended that the PALE Data Management team be expanded and their mission redefined so that they become responsible for the data management of all PARCS data sets and become the interface with the PAGES, ESH and ARCSS data efforts. The PARCS Data Management team should consist of two full time individuals who are responsible for the project's data management and for the day-to day activities of the PARCS Steering Committee.

Primary data compilation is a time-consuming and iterative process involving close interaction with participating researchers. Data generated by PARCS researchers must be identified, requested, and received. Where appropriate, collaborative relationships with other ARCSS, ESH and international researchers need to be established so that the most complete data coverage possible is easily available. Once the data are in hand, they must undergo quality control procedures that require the data coordinator to work closely with the submitting researcher to ensure accuracy and the submission of essential metadata (*e.g.* location information, age control, publications, etc.). Where possible, the data coordinator also will take advantage of extant database efforts (*e.g.* the Global Pollen Database) to compile data for PARCS.

The data coordinator will be responsible for the rescaling of the primary data to create "value added" paleoenvironmental data sets. The rescaled data must then be placed in spatial and temporal context (visualization), the methods of rescaling documented, and the "value added" data products placed into an electronic form that is easily accessible. An example of this would be the conversion of primary pollen data to vegetation categories based on a specified set of rules, and the mapping of these categories for specific time slices.

PARCS is designed to better understand the relationship between temporal and spatial environmental change. If natural and anthropogenic forcing are to be more thoroughly characterized, data sets covering different time scales will be required throughout the circum-Arctic. As demonstrated by the development of the Beringia Atlas, the ability to scale information will be needed to make regional predictions from site-specific studies.

### The PALE/CAPE Atlas

Because of the strong positive response from the scientific community to the Beringian Atlas (Figure 12), PALE is joining with the CAPE/PAGES Project to coordinate data activities and expand the geographic scope of the Atlas to cover the entire Arctic. The on-line atlas format provides an efficient and accessible medium for multi-proxy paleoclimate data and is an effective way for PARCS/PALE to share data with the ARCSS and international scientific communities. The coordination of the Atlas effort consists of two parts: compilation of primary paleoenvironmental data, and the rescaling of the primary data into the paleoenvironmental data sets and their subsequent display.

The PARCS data management and Atlas activities will make use of new and effective communications technologies to ensure that PARCS data will remain useful and available to the scientific and educational communities over the long term. New ways of interpreting data are continually arising, and the data effort outlined here will ensure that raw data and derived data products will be available in the future as required.

## Sample Management

The environmental and ecological systems of the Arctic operate on a wide spectrum of temporal and spatial scales and paleoenvironmental records are derived from a wide variety of natural archives. PARCS is an attempt to apply the full complement of operational and analytical methodologies to regions essential for the completion of a suitable spatial distribution of sites for a better understanding of the Arctic's paleoenvironmental variability.

The primary research material for this effort is "the core" – drill cores, ice cores, lake cores, and marine cores. Each core/site requires highly targeted research protocols to ensure quality control, compatibility of the data collected and a high degree of confidence in the paleo-environmental interpretation (PAGES, 1994). Cores from this array of archives present special challenges in their preservation and archiving. For many studies it is imperative that the cores be kept cold (or frozen) until studies are completed, and specialized equipment is necessary for processing, recording, and analysis.

Because of the nature and degree of detail of the paleo-records investigated, the arctic research community needs to be better served by the creation of a core laboratory and repository that will allow the consistent treatment and preservation of these materials. Ongoing projects and estimates of future needs swamp the storage and analysis capacity of extant facilities. Arctic research projects are returning high quality cores in great number from both conventional coring and newer drilling techniques. It has become evident that the U.S. paleoscience community requires a central, state-of-the-art, facility for the analysis and preservation of these paleoenvironmental research materials. The cost of curating these materials is small compared to the cost of retrieval. Further, for the individual investigator who is central to the paleoscience endeavor, the enhanced standards of multiproxy analyses require facilities (and technical support) that are beyond the capabilities that can be reasonably provided at most universities.

At this time, there is no single facility for the curation of PALE lake and marine cores - essentially each researcher, or group of researchers, is responsible for their own core storage. However, with the success of PALE, many individual university facilities are now reaching or have reached their capacity. In the next 5 to 10 years with the increase of lake coring, and the addition of a strong marine paleo component (*e.g.*, associated with the commissioning of the Coastguard vessel Healy), the community's ability to deal with these materials will far exceed current capacity. It is here recommended, therefore, that a suitable national "Arctic Core Depository" be established by PARCS to allow for the consistent curation of these materials. This need should be well coordinated with other arctic and national paleoscience research activities.

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# GUIDE TO ACRONYMS

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| ACSYS | Arctic Climate System Study (WCRP) |
| ANS | Arctic Natural Sciences Program (NSF) |
| AO | Arctic Oscillation |
| ARCSS | Arctic System Science Program (USGCRP) |
| CAPE | Circum-Arctic Paleo-Environments (PAGES) |
| CLIVAR | Climate Variability and Predictability (WCRP) |
| COMAP | Cooperative Holocene Mapping Project |
| CSM | Climate System Model |
| ENSO | El Niño-Southern Oscillation |
| ESH | Earth System History Program (USGCRP) |
| GAIM | Global Analysis, Interpretation and Modeling (IGBP) |
| GCM | General Circulation Model |
| GISP2 | Greenland Ice Sheet Project-Two (US) |
| GRIP | Greenland Icesheet Project (European) |
| HARC | Human Dimensions of Arctic Change (ARCSS) |
| IASC | International Arctic Science Committee |
| ICAPP | International Circum-Arctic Paleoclimate Program (PAGES) |
| ICDP | International Continental Drilling Program |
| IGBP | International Geosphere-Biosphere Programme (ICSU) |
| IMAGES | International Marine Global Change Study (PAGES) |
| LAII | Land-Atmosphere-Ice Interactions (ARCSS) |
| LOIRA | Land-Ocean Interactions in the Russian Arctic (IASC) |
| MIS | Marine Isotope Stage |
| NAD | Nansen Arctic Drilling Project |
| NAO | North Atlantic Oscillation |
| NGRIP | North-GRIP (European) |
| NOAA | National Oceanic and Atmospheric Administration |
| OAII | Ocean-Atmosphere-Ice Interactions (ARCSS) |
| PACT | Paleoecological Analysis of the Circumarctic Treeline |
| PAGES | Past Global Changes (IGBP) |
| PALE | Paleoclimates from Arctic Lakes and Estuaries (PARCS) |
| PANASH | Paleoclimates of the Northern and Southern Hemispheres (PAGES) |
| PARCA | Program for Arctic Regional Climate Assessment (NASA) |
| PARCS | Paleoenvironmental Arctic Sciences (ARCSS, ESH) |
| PECHORA | Paleo Environment and Climate History of the Russian Arctic |

| | |
|---|---|
| PEP | Pole-Equator-Pole transects (PAGES) |
| PICE | Paleoenvironments from Ice Cores; Bi-Polar (PAGES) |
| PNA | Pacific-North American climate pattern |
| PRB | Polar Research Board (NAS) |
| QUEEN | Quaternary Environment of the Eurasian North (ESF) |
| RAISE | Russian-American Initiative on Shelf-Land Environments (ARCSS) |
| SHEBA | Surface Heat Budget of the Arctic Ocean |
| SIMS | Synthesis, Integration, and Modeling Studies (ARCSS) |
| TEMPO | Testing Earth System Models with Paleoenvironmental Observations (ESH) |
| USGCRP | U.S. Global Change Research Program |
| WCRP | World Climate Research Programme (ICSU) |
| WDC-A | World Data Center-A (for Paleoclimatology) |

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