Toward An Arctic System Synthesis: Results and Recommendations

From the ARCSS All-Hands Workshop
30 April - 3 May 1996
Snowbird, Utah

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Funded by the National Science Foundation
Arctic System Science Program

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This report is published by ARCUS with funding provided by the National Science Foundation under Cooperative Agreement OPP-9404321. The opinions, findings, conclusions, and recommendations contained in this document do not necessarily reflect the views of NSF.

This workshop report may be cited as:
Toward an Arctic System Synthesis: Results and Recommendations. The Arctic Research Consortium of the United States (ARCUS). Fairbanks, Alaska. May 1998. 165 pp.

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Foreword

More than 175 researchers and others active in the first seven years of research supported by the Arctic System Science (ARCSS) Program met in May 1996 in Snowbird, Utah, at the first ARCSS All-Hands Workshop. ARCSS researchers, investigators from other major national and international arctic research programs, and representatives of federal agencies conducting arctic research presented results, assessed the state of the ARCSS scientific enterprise, and worked together to identify future research priorities. At the time of the workshop, I was chair of the ARCSS Committee and was honored to chair the workshop in that capacity.

This report includes recommendations from participants, prepared in three major synthesis groups. The working groups developed interdisciplinary research priorities related to the workshop theme, *Variability of the Arctic System: Manifestations and Mechanisms*, in the following areas:

- Temporal and Spatial Change;
- Environment, Resources, and People; and
- Global Change and the Arctic System.

This report also includes abstracts from the scientific presentations. The workshop strongly emphasized the involvement of graduate students and young investigators and several of the poster abstracts are the products of their work. When this workshop convened, research discussed in many of these abstracts was ongoing, and the work was later published in scientific journals. Many abstracts now include references to published results.

The synthesis recommendations prepared at the workshop were reviewed by the ARCSS Committee and further developed through various discussions with members of the arctic research community. I would like to thank the members of the ARCSS Committee for their work on this report and the workshop participants for their contributions to the content. I would also like to thank reviewers for the many thoughtful comments that have improved earlier drafts, especially Henry Huntington, whose editorial skills helped to refine the workshop report from early draft stages to this final form.

The Arctic Research Consortium of the U.S. (ARCUS) convened the ARCSS workshop and provided editorial guidance for the development of this report. Wendy Warnick, Alison Carter, Diane Wallace, and Kristjan Bregendahl of ARCUS did an exceptional job of planning and coordinating the workshop on behalf of the ARCSS Committee. Anne Sudkamp and Milo Sharp of ARCUS contributed much to the report's development and publication. Finally, I would like to thank the Office of Polar Programs at NSF for financial support for this work and for the opportunity to participate actively in this productive and creative planning process.

W. Berry Lyons
University of Alabama
May 1998

Toward an Arctic System Synthesis: Results and Recommendations

In May 1996 the Arctic System Science (ARCSS) Program convened, for the first time, an investigators workshop. The workshop brought together members of the arctic system science community to determine the state of the overall scientific enterprise undertaken by ARCSS and to make recommendations for future research priorities. Integrating human dimensions into arctic system research was a major part of this effort. The 175 participants included principal investigators, co-investigators, graduate students and post-doctoral researchers, and representatives of related programs. All took an active part, and the birth of new ideas and directions for arctic system science made the workshop an unqualified success.

This report is an overview of the workshop, including summaries from each of the three synthesis groups. The accomplishments of the meeting, however, were far greater than a single document. New inter- and multi-disciplinary connections were made, not just among the ARCSS project complexes, but more importantly among many disciplines and researchers who had not previously had the opportunity to interact so creatively and constructively. We expect that these connections will have a lasting and positive impact.

While the discussions proceeded differently in each group, and thus the summaries are presented differently, the goal was the same throughout: to synthesize ideas and integrate efforts to develop a holistic understanding of the arctic system in the context of the global system. We hope that the ideas from the discussions will be the basis for the next ARCSS science plan. We gratefully acknowledge the efforts of the three group chairs: Julie Brigham-Grette, David Klein, and Gunter Weller.

The Temporal and Spatial Change group emphasized the need to understand better the relationship between temporal change and spatial change. If natural variability, not to mention anthropogenic forcing, is to be thoroughly defined, we need past data sets covering different time scales throughout the arctic region. International collaboration is essential in the pursuit of such data, since no one nation has the resources or logistics support to conduct all the needed research. The group also stressed that the ability to scale information is needed so that regional predictions can be made from site-specific studies.

The Environment, Resources, and People group developed a series of questions relating physical and biological processes and their consequences to human responses. A major theme of this discussion was the importance of land/ocean interactions, especially the variation in freshwater and chemical (both natural and anthropogenic) fluxes on the total arctic system (*i.e.*, ocean, atmosphere, terrestrial, freshwater, human). The influence of biological-to-biological interactions, especially those affected by or affecting humans, was also considered extremely important.

The Global Change and the Arctic System: Assessing and Modeling Impacts group acknowledged the importance of defining and then assessing the impacts of change at differing temporal and spatial scales. An overall understanding of the arctic system must include the arctic impacts of global events and phenomena and the global impacts of arctic events and phenomena. The group identified a series of research and infrastructure gaps that need to be filled in order to develop better arctic assessments and models. While existing models can be used to derive numerous physical and chemical variations, many modeling issues are yet to be resolved and many important variables, especially biological ones, need to be incorporated in future models.

Temporal and Spatial Change

This synthesis group was composed of four working groups: temporal change, spatial change, scaling issues, and arctic system variability. Noting that understanding the nature of past and present climate variability is the key to improving predictions of environmental change for the Arctic, the groups generated four common themes, incorporating both research approaches and coordination needs, as foci for future ARCSS work:

- sensitivity and variability on the contemporary landscape,
- sensitivity and variability through time (emphasis on paleorecords and relation to global change),
- data compilation and archiving (*i.e.*, databases), and
- international cooperation.

Current and future research should be directed toward improving knowledge about the sensitivity and variability of all aspects of pan-arctic systems. An understanding of key processes operating in contemporary landscapes, oceans, and atmosphere provides the best avenue to an understanding of the interactions and interdependencies of these systems in the Arctic. Such work provides a vital basis for constructing numerical or conceptual models of both future and past northern high-latitude earth systems. The models can then provide a strong framework within which hypotheses can be generated for testing by regional-to-global-scale models and by paleorecords.

In addition to examining the contemporary Arctic, we must examine a variety of time scales. Paleorecords are our only source of data from the past. Extending in some cases over millennia, they provide a major mechanism for evaluating the accuracy of various models (*e.g.*, atmospheric, oceanic, and ecosystem) and thereby play a central role in the development of models used to predict future climates. Paleorecords are the only empirical source of insight into the dynamics of significant climatic change and the responses of ecosystems to this change.

There is a critical need for circumarctic databases that can be used to understand the dynamics of spatial and temporal environmental change in the Arctic and to evaluate how well our models simulate these dynamics. Science questions concerning the arctic system require that studies of single sites and small areas (*e.g.*, single catchments) be expanded to subcontinental, continental, hemispheric, and, ultimately, global scales. Regional focus studies, such as those in the North Atlantic region and Beringia, need to be replicated involving principal investigators from projects such as Land-Atmosphere-Ice Interactions (LAII), Ocean-Atmosphere-Ice Interactions (OAII), Paleoclimates from Arctic Lakes and Estuaries (PALE), and ice-core projects in the wake of the Greenland Ice Sheet Program (GISP2). Documentation of the human use of landscapes and seascapes also must be interwoven with such regionally focused studies.

The compilation of such databases and the construction of broad-scale syntheses require international collaboration. Furthermore, the financial and logistical constraints of working in the Arctic require joint partnerships with parallel science programs in other countries. Despite the plethora of acronyms for separate climate system programs, many of these programs have common goals. Hence, it is imperative that alliances be strengthened to ensure efficiency and prevent redundancy. No one country can support all the needed research, nor should one country do so, especially as we seek global-scale strategies for understanding the climate system.

The task of our four working groups was to discuss salient elements of variability in arctic system science and make recommendations for future research. There is broad intellectual overlap among these recommendations, and they should be considered as a whole rather than as discrete units.

Temporal Change

Research across time scales ranging from seasonal to millennial is necessary to develop an understanding of the sensitivity and variability of the arctic system, including terrestrial, marine, coastal, and cryosphere systems. Because high-resolution proxy records of the last 2,000 to 20,000 years may not capture the full range of climate variability or the full land-ocean-atmospheric response to extreme events, low-resolution records going back at least 135,000 years that record such extremes are needed. The need to understand both the sensitivity of, and the variability within, the climate system also requires interconnections among programs studying contemporary processes (*e.g.*, LAII and OAII) and programs on paleorecords (*e.g.*, PALE and GISP2) (Figure 1).

Studies of important contemporary processes are needed not only to understand short-term variability, but also to develop better paleoenvironmental proxies to record the full range of possible climate system behavior. While the physics and algorithms developed in contemporary process studies are needed to describe these processes in global- and regional-scale models, only reliable century-to-millennia-long proxy records (*e.g.*, ice and lake cores) from a spatially broad network of sites can define long-term variability. This long-term variability, in turn, can be used to define patterns that can be used as boundary conditions in climate models.

The interactive process of examining how well models reproduce paleoclimate scenarios provides the only means of validating whether the models can actually simulate realistic climate change. To move further, this process requires new linkages between principal investigators in contemporary process studies such as LAII and OAII, paleorecords being developed by PALE and GISP2, and much needed marine records from the Arctic. Data are needed at a variety of temporal and spatial scales to capture the full range of responses and changes over both the long term and at human scales. These changes require us to look at both the effects of the arctic system on humans and the effects of humans on the Arctic. Such an inquiry is necessary for understanding climate shifts and, most importantly, to make accurate predictions about the effects arctic environmental change and humans, in the Arctic and elsewhere, will have on each other.

To do this work, we need to:

- develop stronger linkages between process studies and the development and use of paleoenvironmental proxies,
- Use paleorecords from networks of sites to evaluate predictive models,
- Develop more linkages between modelers and process-oriented scientists and paleoenvironmental scientists, and
- Develop more linkages between paleoenvironmental scientists and archaeologists and other social scientists to describe the nature of human migrations and adaptations to environmental change.

Spatial Change

An understanding of the temporal scales of environmental change requires a simultaneous understanding of spatial variability in the arctic system, especially if we are to extrapolate our regional understanding of the physical characteristics and dynamics of the arctic system to the global scale. Future research in this

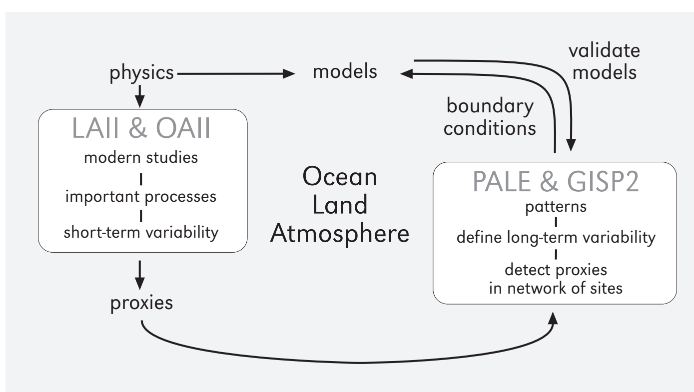

*Figure 1. Interconnections among programs studying contemporary processes (*e.g.*, LAII and OAII) and programs on paleorecords (*e.g.*, PALE and GISP2) advance understanding of climate sensitivity and variability in the arctic system. Contemporary process studies develop evidence for paleoclimate proxies to be extracted from sediments and fossils across a network of sites. The paleorecords define boundary conditions that contribute to climate models and are a means for validating the models. These data also improve the algorithms and physics supplying the models to predict contemporary processes at all levels of the ocean-land-atmosphere system. Figure by Gifford Miller.*

direction should take a two-pronged approach.

First, it must involve continuing and expanding current efforts to document spatial networks of information, for example, developing circumpolar databases such as circumarctic vegetation maps, soil maps, and permafrost maps, as well as geographic atlases of topography and hydrologic networks (*e.g.*, Russian Environmental Atlas). Where possible, these spatially explicit databases should include a temporal dimension to incorporate paleoenvironmental data.

Second, detailed synthesis studies of regional areas must be developed from existing programs in order to pull together diverse multidisciplinary information (Figure 2). Such an approach could be carried out across the North Atlantic region with the collaboration of PALE, GISP2, the European Greenland Ice-Core Project (GRIP), and North Atlantic Biocultural Organization (NABO), plus the Polar North Atlantic Margins Programme (PONAM); across Beringia with the extension of PALE, LAII, OAII, the Bering Sea Impact Study (BESIS), and the Mackenzie Basin Impact Study (MBIS); and, finally, across the Russian shelf with the maturation of the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE) and Quaternary Environment of the Eurasian North (QUEEN).

As an example of such a synthesis, key cross-disciplinary questions can be posed for the Beringian region:

- What was the effect of the Land Bridge and its subsequent flooding on coastal erosion and arctic and global ocean circulation patterns? On regional and global climates?
- How have Beringian landscapes (*i.e.*, vegetation, soils, hydrologic patterns) evolved through time?
- What have been the influences of this evolution on key ecosystems and the components and processes operating in these ecosystems (*e.g.*, trace gas flux, carbon accumulation, energy and water fluxes, biodiversity, hydrology, soil water,

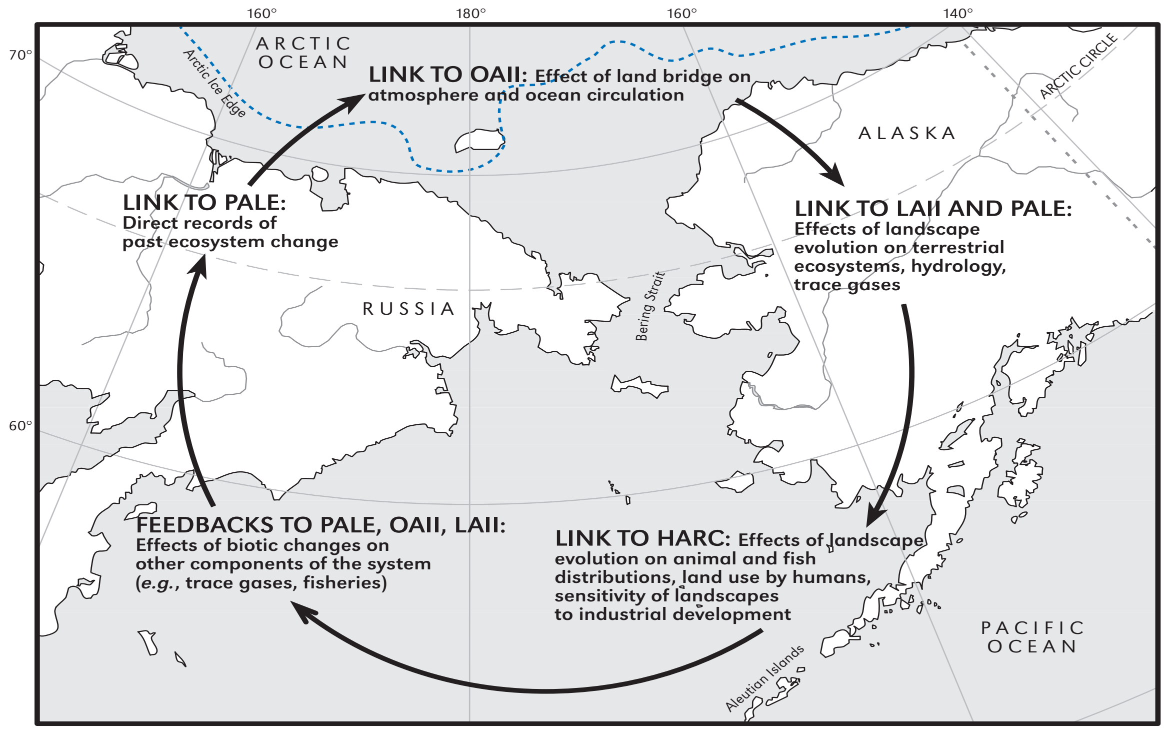

Figure 2. Detailed synthesis studies of regional areas must be developed from existing programs in order to pull together diverse multidisciplinary information. Figure by Donald (Skip) Walker.

permafrost, and the human use of landscapes)?

- How have biotic changes affected feedbacks to global atmospheric and ocean circulation patterns?
- How well can we model the patterns of past change, at scales from a plot up to the subcontinent?
- How will vegetation patterns change under an altered climate? What are the implications for other components (*e.g.*, trace gases, fish, humans, animals)?
- How will climate change affect sea-ice distribution in the Beringian area? What will be the feedbacks to permafrost, precipitation, and trace gas fluxes?
- How does the Beringian region contrast with the North Atlantic or Russian shelves?

Scaling Issues

Scaling in space and time is an integral feature of arctic system science. The results of studies at one scale need to be related to other scales to enable regional and circumarctic predictions. As an inherent part of all ARCSS projects, scaling issues should be addressed explicitly.

In their proposals, all ARCSS principal investigators should:

- state the time and spatial scales of the research explicitly,
- identify how results from the project can be linked to processes and patterns of change on other temporal and spatial scales, and
- where appropriate, state how they will investigate the role of small-scale processes in large-scale models.

Furthermore, information on the temporal and spatial scales of each ARCSS project should be made available on the ARCSS World Wide Web site. This recommendation can be implemented immediately.

Arctic System Variability

A common thread woven through all elements of arctic research and our collective efforts to understand the Arctic as a system is variability. Four major themes capture the compelling science issues facing the arctic community today:

- seasonal-to-interdecadal variability in the arctic system and a means to predict it (*e.g.*, focus of the U.S. Global Change Research Program [USGCRP]),
- the full range of variability throughout the arctic system (*i.e.*, as archived in both terrestrial and marine paleoclimate records),
- how environmental variability affects humans, and
- the role of the Arctic in the global system.

To grasp the complexity of the arctic system, and reduce predictive uncertainties, we must examine a large number of multidisciplinary research elements, including:

- radiative energy fluxes,
- the hydrologic cycle,
- transports across the land/ocean boundary,
- sea-ice dynamics,
- atmospheric circulation,
- carbon cycling,
- ocean circulation,
- geochronology,
- ecosystem dynamics,
- contaminants and tracers,
- anthropogenic impacts, and
- integrative modeling and model verification.

In order to implement investigations along these themes and improve our understanding of each of the research elements listed, we need:

- improved logistics capabilities for the Arctic Ocean and adjacent shelves via modern research platforms,
- a major program to recover marine cores from strategic areas of the Arctic Basin and surrounding shelves,
- the ability to plan and support a number of research elements for periods of more than 3–5 years in order to capture more of the interannual signal in the coupled ocean-atmosphere-terrestrial system, and
- to develop systematic connections with international programs in order to stretch research dollars as far as possible while avoiding redundant science.

Environment, Resources, and People

This synthesis group developed seven primary research questions and discussed their importance, the components needed to answer them, and their connections to humans.

What is the variability of freshwater fluxes (including sea ice) from the Arctic through Fram Strait and the Canadian Arctic Islands and what is its effect on North Atlantic thermohaline circulation?

The large influx of freshwater to the Arctic Ocean from major north-flowing rivers affects Arctic Ocean currents, sea ice, salinity, and corresponding discharge to the North Atlantic in a manner not yet understood. An understanding of this process, however, is crucial for assessing the consequences of variability in the Arctic Ocean system for Arctic Ocean and North Atlantic biological resources and the humans dependent on them. Gaining this understanding will require more detailed knowledge of the dynamics of the freshwater fluxes of the Arctic Ocean.

Essential Research

Essential research to address this question includes:

- integrating and interpreting yearly and seasonal North American and Eurasian River discharge data,
- creating a coupled ocean-ice-atmosphere model of contemporary processes, and
- assessing system response range by integrating historical data, (*i.e.*, over the past 20,000 years).

Significance for Human Welfare

The following aspects of this question may concern human populations:

- the effects of freshwater flux variability on North Atlantic fisheries, and
- the correlation of declines of cod and salmon stocks with great salinity anomalies (Figure 3).

How do shelf dynamics influence distribution in, and export from, the Arctic of freshwater (including sea ice), contaminants, and nutrients, and how do these dynamics impact productivity, including productivity of fish and marine mammal stocks?

Large expanses of the Arctic Ocean north of Russia, Scandinavia, and western Alaska are shallow continental shelf. The dynamics of these extensive shelf regions as they influence water, nutrient, and salinity fluxes in the Arctic Ocean must be better understood in order to describe and predict contaminant dispersal and biological productivity in the Arctic Ocean and adjacent seas. This question involves work under LAII, OAII, PALE, and Human Dimensions of the Arctic System (HARC).

Essential Research

Addressing this question includes:

- tracing the fate of riverine H_2O from shelf to ocean, (*e.g.*, using ^{18}O, ^{13}C, and specific contaminants),
- examining the linkages and interactions among riverine nutrient flux, sediment nutrient release, sea-ice cover, and productivity,
- determining if and how changes in physical processes (sea-ice cover, etc.) affect trophic-level responses that ultimately support fish and marine mammal populations, and
- identifying sources and sinks of sediments across the shelf.

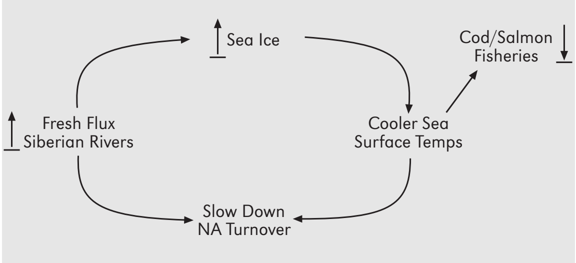

Figure 3. Declines in cod and salmon stocks correlate with great salinity anomalies. Figure developed by Environment, Resources, and People synthesis group.

Significance for Human Welfare

The following aspects of this question may have significance for human populations:

- the effects on fisheries and marine mammal harvests,
- the implications of contaminant flux, and
- sea-ice distribution and northern shipping routes.

How do ocean, freshwater, and atmospheric contaminants relate to the arctic system?

Research studies throughout the Arctic show a disturbing distribution and accumulation of anthropogenic contaminants. These contaminants are concentrated in higher trophic levels, including marine mammals important to the diets of arctic residents. Organochlorines and heavy metals appear to be of particular concern. These findings have raised serious concerns in arctic communities, fueled by the lack of complete or even adequate information. More needs to be known about the origins, transport, concentrations, and effects of a wide range of actual and potential pollutants in the arctic system. Studies of these issues should be linked with and build on the Arctic Monitoring and Assessment Program (AMAP) and the Arctic Nuclear Waste Assessment Project (ANWAP).

Essential Research

Addressing this question includes:

- coordinating research among agencies and disciplines to consider all aspects of a complex problem and to communicate the nature, scope, and results of research appropriately to arctic residents and others,
- examining the transport, uptake, and bioaccumulation of contaminants in the arctic system, including physical and biological mechanisms,
- evaluating climatic effects on the transport and concentration of contaminants,
- identifying the effects of contaminants on marine, terrestrial, and freshwater ecosystems, and
- identifying how contaminants entering the arctic system reach humans and affect human health.

Significance for Human Welfare

Contaminants may have large impacts on human populations, including:

- the potential impacts to resource utilization and subsistence and cash economies,
- the perceived and actual health risks and their consequences, and
- education and public information to address risks.

What are the potential effects of sea-level rise on coastal habitats (e.g., through shoreline erosion/deposition, transport of sediment and contaminants, and permafrost degradation)?

Coastal geography surrounding the Arctic Ocean is expected to change with climate-mediated sea-level change and increased wave influence due to reduced sea-ice cover. Coastal erosion and deposition, the transport of sediment and associated contaminants, and coastal fringe permafrost degradation will affect the infrastructure, transportation, resource exploitation, economic well-being, and health of residents of northern communities. These physical changes in coastal areas will also affect the biological productivity and species composition of inshore lagoons, deltas, and estuaries.

Essential Research

Addressing the effects of sea-level rise on coastal habitats includes:

- examining eustatic and isostatic components,
- correlating changes in estuarine circulation with Holocene sea-level rise, and
- examining and predicting changes in estuarine productivity and coastal vegetation.

Significance for Human Welfare

To understand impacts of sea-level rise on human populations, the following are needed:

- a better understanding and prediction of changes in water resources/aquifer salinization, and
- a better understanding and prediction of changes in habitat for subsistence resources.

How has the land-shelf system responded to variable environments in the Holocene?

The land-ocean shelf interface in the Arctic Basin has responded to variations in climate and sea level during the Holocene. Focusing research on paleontological and archaeological evidence of sea-level change, plant community responses in the Arctic Basin, and patterns of human settlement and associated resource exploitation in coastal areas will provide a basis for predictions of whole-system responses to environmental change in the Arctic. The components of this research should be considered over a range of temporal scales. Studies of the glacial interval (20–30 ka) can examine how northern ice sheets affected river flows, what the effects were on North Atlantic inputs, and the characteristics and impacts of massive changes in the hemispheric hydrologic system. Studies of the Holocene (10 ka) can help us understand the current interglacial interval. Studies of the last 500 years can give higher resolution from the Little Ice Age to more recent warming. Studies of contemporary processes and fluxes can further describe and quantify current variability and provide clues for understanding data from the past.

Essential Research

Essential research to address this question includes:

- examining the response of the tree-line and concomitant changes in surface hydrology and fluxes to the shelf,
- examining the response of marine biota and human populations, and
- correlating changes in riverine flux, nutrient availability, and sea-ice cover.

Significance for Human Welfare

The following aspects of this question may affect human populations:

- changes in the resource base, and
- changes in landscape (*e.g.*, habitat changes).

How will global change influence trophic interactions?

Global change in the Arctic will undoubtedly influence trophic levels differentially, although any major change within a trophic level will affect the dynamics of intertrophic relationships.

Essential Research

Addressing the question of trophic-level change includes:

- examining the response of aquatic and terrestrial primary and secondary producers to global change,
- examining the interactions between primary and secondary producers, and
- examining changes in harvest by secondary producers resulting from changes in their dynamics.

Significance for Human Welfare

The following aspects of these changes may affect human populations:

- changes in subsistence hunting success, and
- the relationship between changes in economic base, social institutions, and harvest of subsistence resources.

For the next half century, how can the benefits (social, cultural, economic, environmental) of resource harvesting and extraction in the Arctic be maximized and negative consequences be minimized?

Aspects of global change are related to the development and sustainability of arctic resources and their consequences for people inside and outside the Arctic who depend on those resources. The study of these aspects will benefit both groups. While this topic has politically charged implications, it is also a fundamental system science matter firmly within current NSF program emphasis.

Essential Research

Addressing the question of maximizing benefits and minimizing negative consequences includes:

- conducting comparative and retrospective studies as a basis for policy, management, and planning, and

- evaluating status and trends for non-renewable and renewable (both living and non-living) resources.

Significance for Human Welfare

Concerns for human populations include:

- the potential impacts—direct, indirect, and cumulative—on jobs, infrastructure, habitat, permafrost, contamination, biodiversity, revenues from oil and gas development, and so on (see Table 1, page 10).

Global Change and the Arctic System: Assessing and Modeling Impacts

This synthesis group noted numerous questions and issues related to the nature of impact assessment, including the interactions between global change and change in the Arctic. For example, arctic-triggered changes may affect global thermohaline or atmospheric circulation (Figure 4), and global greenhouse warming leads to melting permafrost in the Arctic. These and more complex interactions, often back and forth between global and arctic systems, underscore the difficulties in identifying, assessing, and modeling impacts.

Cause \ Effect	A	G
A	1 A → A	2 A → G
G	3 G → A	4 G → G

A = Arctic, G = Globe

***Figure 4.** Cause-effect matrix for arctic and global interactions. Figure provided by Gunter Weller.*

The questions that were raised and the discussions they stimulated are reflected in the points outlined below.

Temporal Scales

Four time scales were considered important for impact assessments:

- Seasonal-to-interannual (1–5 years) covers the El Niño-Southern Oscillation (ENSO) time frame for which some forecasting ability exists.
- Decadal (10–20 years) is the time scale of immediate practical concern to most stakeholders. Predictions over this time scale are considerably more difficult than over the 1–5 year time scale.
- Century (100 years) is the greenhouse-effect time scale of interest to scientists and climate modelers and the time scale for significant human impacts stemming from such processes as sea-level change and soil-fertility change.
- Over longer time scales some effects of global change, (*e.g.*, transport and bioaccumulation of certain contaminants), will be felt and must be considered in impact assessments (see also Table 1, page 10).

Spatial Scales

The scope of impact assessments relevant to ARCSS is pan-arctic. Because of the difficulty of this undertaking, there should be, at least initially, a focus on areas of particular interest. Such areas can be identified, for example, on the basis of climatic anomalies. While most arctic land masses have experienced considerable warming over the last few decades (Intergovernmental Panel on Climate Change (IPCC), 1996), the eastern part of Canada and southern Greenland have cooled. The circumpolar vortex and planetary wave pattern not only influence these climatic anomalies but also affect atmospheric pollutant transport and should be considered in choosing appropriate areas for impact assessments. It will be desirable to start with regional approaches such as those proposed by the International Arctic Science Committee (IASC) for the Barents and Bering seas. Within a particular region, however,

Hydrocarbon Extraction Example	Time Scales			
	1–5y	20y	100y	>100y
Phases				
Environmental impact statement & design	✓			
Operational		✓		
Post-operational			✓	✓
System Science Activities				
Baseline description & monitoring	✓	✓		
System dynamics	✓	✓		
Retrospective studies of benefits & consequences	✓	✓		
Modeling & integrated assessment		✓	✓	✓

Table 1. Time scales of 1–5 years, 10–20 years, 100 years, and longer term are all considered important for impact assessments. In this hydrocarbon extraction example, study of development phases fall in different time scales, as do system science activities. Table developed by Environment, Resources, and People synthesis group.

orographic and coastal influences result in significant variations over scales of 100 meters or less.

Impacts to be Addressed

Both arctic and global impacts were considered to be relevant. A number of key impacts, local as well as global, were identified and are discussed in the next section and listed, along with the affected stakeholders and the parameters needed to measure them, in Table 2.

Stakeholders/Users

Many people have a stake in the Arctic and are thus potential users of impact assessments. They include:

- Arctic residents, including indigenous and other people, both rural and urban. Indigenous people face threats of changes to their traditional ways of life and patterns of resource use when snow, sea-ice, and permafrost conditions change. Changes in living conditions (*e.g.*, housing, transportation, health, sanitation, etc.) will affect all residents.
- Users of arctic resources, including local as well as distant consumers and industries utilizing renewable and non-renewable resources. The Arctic is an important global source of petroleum and fish. Oil and gas reservoirs exist in Russia, Canada, and Alaska, and the Bering Sea remains one of the world's most important fisheries. Environmental changes in these regions may affect the production, transportation, availability, and, consequently, the cost of these resources to the local and global community.
- Ecosystems and wildlife are stakeholders, too, since change will affect them. A change in climate will cause changes in the supply of nutrients and energy. There may be further human encroachments and disturbances of habitats and ecosystems, and increasing contamination may have greater effects.
- Global community. Not only will access to arctic resources and their cost affect the global community but other changes in the Arctic will also have global consequences, for example sea-level rise due to the melting of high-latitude glaciers and ice sheets. Glaciers along the Gulf of Alaska have been major contributors to sea-level rise in the past. Arctic feedback processes (albedo, clouds, trace gases, thermohaline circulation, etc.) will also affect the global climate.
- Future generations. Many issues connecting the Arctic to the global system will affect

future generations, including rising population pressure, resource depletion (*e.g.*, water and soil), increased pollution and contamination, and reduced biological and cultural diversity.

Data and Parameters Needed

In order to carry out impact assessments on the likely problems identified above, scenarios and models have to be constructed, and doing so will require data. Some of the key input parameters have been identified in Table 2, although these primarily cover the physical environment. Similar parameters need to be identified for biological and human factors.

Research Needs

Current and proposed studies through LAII, OAII, PALE, GISP2, and HARC, as well as through other national and international research projects, provide data and information for impact assessments. Additional data will be needed, however, and the following areas need further research:

- thermohaline ocean circulation, albedo, cloud, and trace gas feedbacks,
- past climates from high-resolution sediment records in the Arctic Ocean,
- soil processes, carbon stocks, and fluxes,
- biotic responses to climate change, including regional variability and effects on biodiversity,
- the sea-ice regime and the biotic response to sea-ice loss in the Arctic Ocean,
- the rapid climate change event 8,000 years ago,
- seasonal changes (not summer only), and
- coastal zone processes.

Infrastructure Needs

In addition, there is a need for improved arctic infrastructure, including:

- access to and instrumentation for long-term monitoring of environmental parameters (glaciers, permafrost, etc.) to detect change,
- coordination of logistics platforms (ships, aircraft, camps, communities, etc.), and
- coordination between stakeholders/users and researchers.

Stakeholders & Users	What Affects Them? (Problems and Issues)	Needed Parameters for Assessments
Arctic Residents	Availability of marine and terrestrial animals; living conditions (transportation, residence, refrigeration, health sanitation, contaminants)	Sea ice, ocean, snow, permafrost data; water, solar radiation
Users of Arctic Resources	Transportation, construction (offshore and onshore), energy and water (utilities), waste management	Permafrost, ground T, snow, atmosphere, and ocean circulation (pollutants), sea-ice extent
Ecosystems and Wildlife	Nutrient and energy supply, human encroachments and disturbances of habitats, contaminants	Sea ice, permafrost, snow, hydrological cycle, site characterization, biodegradation factors
Global Community	Sea-level rise, feedbacks on global climate (thermohaline, albedo, trace gases, resource availability, and cost)	Solar radiation, soil moisture and fertility, temperatures, ice and snow extent, NDVI, ocean color, atmosphere and ocean circulation, and chemistry
Future People/Populations	Population pressure, resource depletion, biodiversity, cultural diversity	Glacier mass balance, numerous climate parameters (water/energy fluxes), permafrost

Table 2. Different stakeholders and users have different concerns; a variety of parameters are needed to assess impacts on them. Table developed by synthesis group on Global Change and the Arctic System: Assessing and Modeling Impacts.

Modeling

To help with impact assessments, numerous questions were posed by the modelers:

- What do arctic stakeholders need from models and how can system modeling draw on the knowledge of the stakeholders?
- What are the robust temporal and spatial variations of the arctic system (these variations must be verifiable)?
- What controls these temporal variations of the arctic system? For example, do they arise from feedbacks, self-regulation, external forcing, etc.?
- How do variations in the hydrologic cycle of the Arctic influence the North Atlantic Ocean and the thermohaline circulation?
- What is the net flux of carbon when integrated across the surface of the arctic system (all components)?
- How accurately do models simulate the distribution of permafrost and the active layer, and what changes do they project?
- How rapidly will the arctic pack ice disappear (or will it)?

A variety of models and types of models are available to help answer these and other relevant questions that are crucial in impact assessments of global change effects in the Arctic. To use these models effectively and to develop new and better models, there are several issues that need to be resolved, including:

- quantification of uncertainty,
- spatiotemporal characteristics,
- model-to-model validation, and
- limits of predictability.

N xt Steps

Taken together, the w
r shop discussions and re
lting them
s and recommendations clearly point to the nee
for greater interaction among arctic sys
em scientists. Research should be coordinated not only within disciplines and geographic area
but among disciplines, programs, and regio
s. The data we have collected so far should be used to test models, to fill gaps, and to spur productive interdisciplinary collaboration by seeking new uses for those data. This coordination will require additional analysis and organization so that databases are accessible and usable by a variety of researchers in various disciplines. We also need to gather new data, whether from contemporary processes or through paleorecords, to extend our knowledge, to test our hypotheses, and to promote great collaboration through shared data sets gathered with many uses in mind.

Arctic system science is by definition an integrative undertaking. No one researcher can examine all physical and biological processes throughout the Arctic both in the present and back through time. On the other hand, no single study or project complex can answer the broad, fundamental questions about change in arctic and global systems. Only through integrating the planning, conduct, and results of our work can we move toward a better, holistic understanding of the nature and functioning of the arctic system. Such a program must (1) consider the full range of temporal and spatial scales available to us, (2) consider interactions with residents of the Arctic and other users of its resources, and (3) attempt to predict and quantify the nature, extent, and impacts of changes to the arctic system.

The ARCSS Program has made and continues to make a substantial contribution to our understanding of the arctic system, its complexity, and the far-reaching implications of arctic change. To increase our understanding, the project complexes within ARCSS must work closely with one another, and the program as a whole must coordinate its efforts with those taking place elsewhere in the Arctic. Only by a coordinated, committed, concerted effort can we advance the state of arctic system science.

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Snow Working Group Findings

An evening meeting was held during the ARCSS All-Hands Workshop at Snowbird to explore the role of snow and snow cover in the Arctic. The meeting addressed two questions:

1. What impact does snow have on the arctic system?
2. What pressing issues related to snow and snow cover need to be solved?

Dr. Matthew Sturm chaired the meeting and eighteen people participated. A summary of the meeting discussion follows.

Three premises concerning snow were proposed and generally accepted:

Premise 1: Snow covers arctic environments all or most of the year and therefore is a major element of the arctic system, and

Premise 2: Snow itself is generally of little interest to residents and researchers, but

Premise 3: The impact of snow is of great interest.

The group next addressed the question, Where and how does snow impact the arctic system?

Six systems were identified:

- climate
- terrestrial
- oceanic
- glacial
- biological
- human

The group identified a number of direct snow and snow-cover impacts for each system. In some cases, like impacts on terrestrial and oceanic systems, there was considerable overlap.

Climate Impacts

- Snow controls surface albedo during much of the year and, therefore, dominates surface energy exchange.
- Snow has a relatively low thermal conductivity and, therefore, reduces sensible heat losses from the ground.
- Snow reduces surface roughness and therefore turbulent heat transfer.
- The presence of snow changes evaporative rates and processes, as well as moderating freshwater transfer between terrestrial and oceanic systems.

Terrestrial Impacts

- Snow controls the energy and moisture exchange from the land surface for 7 to 12 months of the year.
- Snow controls the thermal evolution of permafrost through changes in the sensible heat transfer.
- Snow controls the enrichment of the active layer through thermal regulation of active-layer depth and supply of water/nutrients.
- Snow indirectly controls stream channel pattern, morphology, and fluvial processes through thermal controls on permafrost and active-layer thickness.
- Snow accounts for 30% to 60% of the annual runoff.
- Snow scavenges pollutants and contaminants from the atmosphere during the winter and concentrates their release during the spring melt.
- Snow-bank processes (nivation) exert a major control on arctic land forms and geomorphology.

Oceanic Impacts

- Most of the terrestrial energy/moisture exchange impacts also apply for snow on sea ice.

- Snow runoff provides the freshwater input to the coastal zone.
- Snow provides the freshwater source for sea-ice desalinization, and the formation of meltwater ponds.
- Snow controls sea-ice thickness through moderation of energy exchange processes.
- Snowmelt provides the freshwater for the mixed layer beneath the sea ice and therefore affects under-ice biological activity.

Glacial Impacts

- Snow is the dominant constituent of glacial systems.
- Snow accumulation rates are preserved in glacial strata and indicate paleoclimatic precipitation regimes.
- Snow controls the albedo, which controls how much melt takes place; therefore snow controls the mass balance of glaciers.
- Snow functions as a trap for gases, dust, aerosols, and other materials; these are the basis of dating and paleoclimate reconstructions in ice-core analysis.

Biological Impacts

Small Animals

- Snow provides a thermal buffer from low winter temperatures.
- Snow can provide a protective cover from predators (depending on snow character).
- Snow prevents animal desiccation due to evapotranspiration.
- Snow distribution patterns determine species distribution and movement.
- Snow conditions the ground temperature and thereby affects overwintering success.
- Snow (and snow character) provides roosting locations.
- Snow-cover onset/melt is a major input in the timing of molting and rearing of young.

Large Animals

- Snow conditions have a major impact on locomotion and hunting success for large predators.
- Snow provides maternity dens (seals, bears).
- Snow can be an impediment or aid to hunting and travel (foxes, wolves, wolverines).
- Snow influences access to forage for herbivores (caribou, musk oxen, arctic hares, ptarmigan).

Snow depth, density, stratigraphy, hardness, and the effects of wind redistribution all play an important role in determining if forage will be accessible or not.

Participants noted that:

a) the timing of the first snowfall and the onset and completion of snowmelt have profound effects on animals, particularly in the timing and route of migration and location of calving; and

b) the distribution of snow depth and snow characteristics (density, grain size, iciness, strength, adhesion, etc.) have a major impact on the winter distribution of ranging species like caribou.

Plants

- Snow cover controls winter thermal conditions experienced by the plants, leaves, and roots.
- Snow-cover thickness and distribution impacts the length and timing of the snow-free period, plus under-snow light conditions.
- Snow impacts/moderates the desiccation, erosion, and damage of plant foliage due to wind and blowing snow.
- Snow processes (depth hoar formation) can cause under-snow desiccation of mosses and other plants.
- Snow loading can cause prostration and breakage of woody plants; snow avalanches can kill plants/shrubs.
- Snow drifts prolong the runoff period and provide water to snow-bed communities.
- There is a close relationship between snow distribution and plant community distribution, with feedback processes and links going both directions.

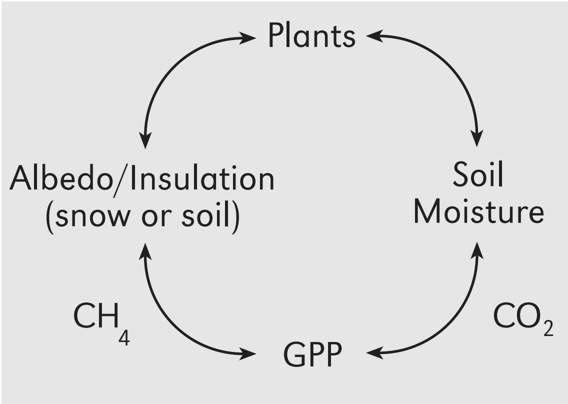

Figure 1. Complex snow/plants/soil cycle. Figure developed by Snow Working Group.

Participants discussed the complex cycle of plants, soil, and snow and diagrammed it in Figure 1.

Human Impacts

Small and Traditional Groups

- Snow impacts human travel and methods of transportation.
- Snow impacts tracking/hunting success.
- Snow controls visibility, enhancing or diminishing contrast and enhancing or diminishing visibility through blowing snow, which in turn impacts hunting success and safety when traveling.
- Snow accumulation can create human hazards or inconvenience through avalanche release.
- Snow requires labor (shoveling, sweeping, sanding for traction, etc.).
- Snow provides material for shelter.
- Snow provides a basis for recreation (skiing, snowmobiling).
- Snow can disrupt community functions through impacts on transportation.
- Snow provides a source of water.

Participants noted that:

a) often the timing of snowfalls or the onset/melt of snow cover has the most profound effects on the impacts listed above, particularly for transportation and seasonal shifts in transportation modes; and

b) the full range of snow characteristics (depth, density, grain size, iciness, strength, adhesion, etc.) affects all of the impacts listed above.

Larger Groups and Infrastructure

- Snow causes disruption of commerce and industry through its adverse impact on transportation, safety, and visibility.
- Snow is a major source for domestic and commercial water resources either directly or in controlling river runoff.
- Snow affects winter travel ability and safety (*e.g.*, over-snow tractor-trains; canceled airline flights).
- Snow management and control requires significant energy and financial resources.
- Historical snow information affects building codes, insurance rates, cost of construction, and the timing of construction.

Participants then addressed the questions,

1. What issues and areas (related to the larger ARCSS issues) require progress in snow research?
2. What questions related to snow are currently unanswered?

Because the snow meeting conflicted with a meeting held by the GISP ice-coring community, the chairman (M. Sturm) went to the Ice Coring meeting and canvassed the group concerning additional research needed in areas related to snow. The issues of importance to this group differed from those developed by the snow group. The ice-coring community still is chiefly interested in snow-process questions relating to the entrapment and immobilization of gases, particulates, and aerosols within the snowpack. They also are interested in the mechanical processes that take place as snow is compressed into firn. Since snow on ice caps tends to have a high degree of lateral homogeneity, the issue of snow distribution, identified as a central issue at the snow working group meeting, was of less importance to the ice-coring group.

The major issue raised by the snow group in relation to research was developing the ability to map, measure, and model the temporal and spatial variability of snow cover. Knowledge gained in these ways is needed to understand terrestrial systems, oceanic systems, and plant and animal distribution, and to assess snow impacts on humans. The issue is being addressed in LAII, will be addressed in SHEBA, and may have relevance to interpretation of results from PALE.

The issues of snow drifting, snow sublimation, and snow transport were raised within the general category of snow distribution. Many process-level components of this problem still are not understood. The absence of trees throughout most of the Arctic gives rise to snow covers that are almost universally affected by wind transport. Drifting impacts plants, animals, humans, sea ice, the terrestrial system, and even the glacial system.

Allied to snow distribution and drifting is the difficulty in making accurate measurements of snow depth and snow water equivalent (SWE). Archived data on snow generally is assumed to be accurate, but that may be an erroneous assumption. An assessment of the accuracy and validity of existing data and active data collection systems has yet to be done. This problem has a particularly strong impact on modelers who rely on the data but who often are not in the position to assess its accuracy.

Accurate knowledge of snow distribution is central to many studies and efforts in ARCSS, which leads to the question of remote sensing. Remote sensing has shown promise for large-scale delineation of snow distribution, but currently no operational methods exist, particularly for the Arctic. The absence of such a tool impacts all areas of arctic studies.

Snow as a reservoir and transport medium for contaminants and pollutants was identified as an issue whose importance probably will increase with time. Clearly, this area has direct impacts on plants, animals and, of course, humans at the top of the food chain.

Lastly, a set of issues relating to snow cover and climate were raised. Insufficient research has been done in these areas making it difficult to assess fully the impact of arctic snow:

1. retrospective and modeling studies of the timing of first snow and snowmelt, and the wider implications for the global climate system of variations in these dates in the Arctic,
2. radiative transfer of snow-covered surfaces,
3. the relationship of snow cover and cloudiness,
4. patchy melting and the interaction of snow and vegetation (or snow, melt ponds, and sea ice) on albedo at regional scales,
5. the relationship of the onset of snowmelt and the atmospheric mean temperature, and
6. dust and other albedo-altering materials on snowmelt, and the ramifications of variations of global dustiness in the climate record on feedbacks through snow-cover albedo.

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Presentation Abstracts

The following two sections list abstracts from oral and poster presentations from this workshop. Abstracts in each section are in alphabetical order by first author. The workshop strongly emphasized the involvement of graduate students and young investigators, and many of the poster abstracts are the products of their work. When this workshop convened, research discussed in many of these abstracts was ongoing, and the work was later published in scientific journals. Many abstracts now include references to published results that provide additional information on this work. Abstracts also include contact information for authors, including institution affiliation at the time of the workshop and, when different, current contact information.

A Multidisciplinary Look at the Arctic Ocean

Knut Aagaard[1] (University of Washington)

During July–September 1994, the ice breakers CCGS Louis S. St-Laurent and USCGC Polar Sea obtained the first scientific section across the Arctic Ocean. The objective was to illuminate the biological, chemical, and physical systems that define the role of the Arctic in global change. The results are changing our perceptions of the Arctic Ocean.

Physical and chemical studies required to define ocean circulation:

- The intermediate layer of the Arctic Ocean has warmed 0.5–1.0∞C in the last few years, and there have been large displacements of water masses, including the Pacific waters.
- A large bolus of relatively cold freshwater with high CFC concentrations, centered at 1000 m in the Makarov Basin, may be the first direct observation of new high-density shelf water within the deep Arctic Ocean.
- Ice rafting of sedimentary material from the shelf regions is likely an important mechanism for supplying reactive trace metals, including iron, to the interior surface waters of the Arctic Ocean.
- Excess alkalinity from river runoff calcium occurred at all stations except those in the Nansen Basin, where most of the near-surface freshwater must therefore come from melting sea ice.

Biological studies needed to determine the carbon cycle:

- Estimated annual production in the central Arctic is 12 g C/m^2, which is tenfold greater than previously published rates. Since we missed peak (bloom) activity of both the ice algae and the phytoplankton, the actual production is likely still higher.
- Bacterial and protist biomass accounted for about 30% of total POC, and at times bacterial production exceeded primary production.
- Estimates of the sinking of POC from the upper waters using naturally occurring Th-234 as a tracer yield rates similar to those deduced from sediment traps. The highest fluxes occurred near Bering Strait, with much lower ones in the central Arctic. A portion of the POC was reaching the sediment, and organic carbon in the top cm was as high as 1% (wt/dry wt).

Contaminant studies required to assess anthropogenic impacts on the marine environment and the food chain:

- The predominant sources of radionuclides in the Arctic Ocean are atmospheric weapons testing (upper ocean) and European reprocessing plants (Atlantic layer).
- Sea ice is likely the dominant vehicle for dispersing radio-contaminated sediments across the Arctic Basin.
- Hexachlorocyclohexane (HCH) is declining rapidly in the global atmosphere, but not in the Arctic Ocean which is now a source of HCH to both the global atmosphere and the Atlantic Ocean.

Measurements of the properties and variability of the ice cover and of the surface radiation budget:

- Much of the ice surface is degraded in such a way that it radiometrically mimics snow, resulting in very high albedo.

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ORAL PRESENTATIONS

- The albedo was as high as 0.30 for shallow melt ponds, while floors of deeper ponds were commonly candled to depths of 10–20 cm, with albedo as low as 0.09.
- Ice concentration maps using a new algorithm with 85.5 GHz SSM/I imagery offers twice the spatial resolution of the traditional NASA Team algorithm based on the lower frequency channels, and the maps show better agreement with surface ice observations.
- Volume scattering by snow can influence the microwave signal measured from space, especially at higher frequencies.

Studies of atmospheric chemistry affecting climate and the upper ocean:

- A substantial fraction of sulfur particles in the lower arctic atmosphere are of biogenic marine origin, particularly on the Pacific side of the Arctic. These particles condition cloud optical properties such as solar reflectivity.
- Measurements of organohalogens will allow us to estimate the contribution of the northern ocean to the chlorine, bromine, and iodine available for ozone destruction in the upper atmosphere.

Geological observations which contribute to reconstructing past climate:

- Sediment on and in ice was observed and sampled along the entire track to the Pole, but was notably absent in the Amundsen and Nansen basins. Microfossil evidence indicates circumarctic shallow shelves as the sediment source.
- Entrained sediment was invariably associated with granular (frazil) ice, which forms during the earliest stages of ice growth. Bulk samples of ice-rafted sediment consisted mainly of silt- and clay-size particles, with only very small fractions of sand.
- The radiogenic isotopes of Sr, Pb, and Nd indicate that the sediment sources for the Arctic Ocean during times of glacial sedimentation had a greater supracrustal component and/or were older than the sources during sea-ice sedimentation. The Sr isotope distribution in the Arctic Ocean is homogeneous and identical to that of the lower latitude oceans, whereas the Pb and Nd isotopes indicate that the end-member crustal sediment sources for the Arctic Ocean are significantly different.

Large, Rapid, Abrupt Climate Changes of the Past—and the Future?—in the GISP2 Ice Core

Richard B. Alley[1] (Pennsylvania State University)

The GISP2 deep ice core from central Greenland, and the companion GRIP ice core, are yielding an exceptionally high-resolution, multi-parameter history of climatic changes over the last 100,000 years or more. The simple lesson is that the historical record does not sample the full variability of the climatic system, during warm times or cold, in the North Atlantic or over much broader regions. Here, I summarize results of the core, together with a very abbreviated set of references.

The GISP2 core was dated by annual-layer counting beyond 40 ka, and then by correlation into the SPECMAP time scale (Alley *et al.*, 1993; Bender *et al.*, 1994; Meese *et al.*, 1994). Repeat counting, using different indicators, and comparison to independent time markers indicates dating uncertainty of roughly 1% in the Holocene and a few percent in the late glacial. Accumulation rates were estimated by correcting for flow thinning and for density change (Cuffey and Clow, 1997), with additional errors of essentially zero at the base of the firn to roughly 15% at 40 ka BP. Accumulation-rate data can be used to assess changes in ice-core chemical and dust loading caused by dilution effects (Alley *et al.*, 1995). Thermometry used a variety of techniques (Shuman *et al.*, 1995), but especially joint interpretation of borehole temperatures and oxygen-isotopic ratios (Grootes *et al.*, 1993; Cuffey *et al.*, 1995; also Johnsen *et al.*, 1995) and now the isotopic composition of trapped gases (Severinghaus *et al.*, 1996), and revealed temperature changes much larger than previously suspected. Records of atmospheric chemistry, gases, volcanism (Zielinski *et al.*, 1994), etc., were generated.

Comparisons between the GISP2 and GRIP cores, with other cores and with instrumental weather records indicate that climatic signals can be detected above noise even for small, year-to-year variations in isotopic temperatures, etc., and that large, rapid, or long-lived changes are primarily signal, not noise (Taylor *et al.*, 1993; White *et al.*, 1997). Work underway may allow separation of changes of ice-core chemical and dust loadings into changes at the source, changes in the source location, and changes between the source and GISP2 (Biscaye *et al.*, 1997); the changes at major climatic steps are so large that they must involve events extending well beyond Greenland (Mayewski *et al.*, 1993).

Major results from the ice core include documentation of large climatic changes (23° C warming, 4–5 fold accumulation-rate increase, 10–100 fold drops in dust and sea salt since the glacial maximum; Mayewski *et al.*, 1994; Cuffey *et al.*, 1995) that often were abrupt (1/3 to 1/2 of the glacial-interglacial amplitude in decades or less to as little as a single year, with “flickering” behavior often observed; Taylor *et al.*, 1992), and were regional-to-global (synchronous or near-synchronous changes observed in indicators of local climate such as temperature and accumulation, of regional climate such as wind-blown sea salt and dust, and of regional to perhaps global climate such as methane; Chappellaz *et al.*, 1993; Brook *et al.*, 1996; Severinghaus *et al.*, 1996), plus similar events seen in records from elsewhere including the Antarctic (Bender *et al.*, 1994; Mayewski *et al.*, 1996). Climate-change events were largest in the ice age, but events larger than those of the historical record occurred during the modern warm period (the Holocene) after warming to or above recent levels and after loss of most or all of the mid-latitude ice sheets (O’Brien *et al.*, 1995; Alley *et al.*, 1996).

The regional-to-global aspects show that these events were widespread reorganizations of the ocean-atmosphere system, not gradual changes such as the slow northward migration of the polar front. The events appear largest and most square-wave in character in the Arctic and subarctic North Atlantic basin, indicating an important or controlling role for this region. Changes in the thermohaline circulation almost certainly were involved (Fawcett *et al.*, 1995 and 1997). Forcings of Holocene events may have been of the same magnitude as possible future forcings in a greenhouse-warmed world.

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In summary, climate changes on a regional-to-global scale have been larger and faster than those in historical experience. Available evidence does not allow us to exclude the possibility of recurrence.

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Temporal and Spatial Variability in the Arctic System: The Arctic Ocean and its Links to the Marginal Seas

John T. Andrews[1] (INSTAAR and University of Colorado-Boulder)

This review focused on the potential interactions between changes in the surface oceanography of the Arctic Ocean and the impact of these on the marginal seas "downstream" from the Arctic Ocean, namely the area of the east Greenland shelf and the eastern Canadian arctic shelves. The time scale of interest is the last 20,000 years or so. Present-day observations indicate that the thermohaline circulation, whereby warm salty water is advected northward where it cools and sinks in the Greenland/ Icelandic/Norwegian seas, is sensitive to relatively small perturbations in the freshwater flux from the Arctic which can be attributed to several mechanisms (Aagaard *et al.*, 1991; Dickenson *et al.*, 1988; Serreze *et al.*, 1992). However, on paleo time scales which involve GISP2 and PALE there is a tendency to look for disruption of the thermohaline circulation from mid-latitude sources associated with the melting of the great Northern Hemisphere Ice Sheets, and the Laurentide Ice Sheet in particular (Broecker *et al.*, 1989). However, Mercer had earlier noted the importance of ice and meltwater fluxes from the Arctic (Mercer, 1969). Looking at the inputs and outputs of freshwater into the Arctic Ocean on the last 20,000-year time scale, the following changes occurred, or may have occurred, and need to be taken into account in any linked atmosphere/ocean model attempting to hindcast changes:

1) The opening of Bering Strait ca. 11 ka, thus allowing relatively fresh Pacific water to enter the Arctic Ocean;
2) Variations in the influx of Atlantic water;
3) The delay in opening of the Canadian Arctic channels until 9 ka and their subsequent reduction in volume outflow due to glacial isostatic uplift of the shallow sills;
4) Item #3 above suggests that the flux of freshwater through Fram Strait has been variable and has probably increased over the last few thousand years;
5) Between ca. 16 and 8 ka large volumes of freshwater were contributed to the Arctic (Andrews *et al.*, 1993; Stein *et al.*, 1994); and
6) Variations in the outflow of rivers into the Arctic Ocean (Mysak and Power, 1992) have probably varied significantly on 102–103 year time scales.

High-resolution records (decadal-to-centuries resolution) of variations in $\partial^{18}O$ in *planktic foraminifera* from the Arctic Ocean, and from the shelf areas downstream off east Greenland and the eastern Canadian Arctic (Andrews *et al.*, 1994; Jones and Keigwin, 1988; Stein *et al.*, 1996) will provide critical data to map out the spatial and temporal variations of freshwater fluxes, a measure of considerable significance to ARCSS.

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Land-Atmosphere-Ice Interactions (LAII)

F. Stuart Chapin, III[1] (University of California Berkeley)

ORAL PRESENTATIONS

The overall goal for LAII is to enhance our understanding of the land-atmosphere-ice interactions in the arctic system, the role that these processes play in the whole earth system, and the effect that global change may have on the Arctic. The scientific questions of LAII are organized under four main themes:

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

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

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

There have been some 25 research projects within LAII since its inception in 1991. Half of these are integrated into a study of trace gas fluxes in northern Alaska. These studies have demonstrated that tundra may be a source or a sink for CO_2 in summer, but a net source in winter, whereas measurable CH_4 flux occurs only in summer. The dominant environmental controls over fluxes of water, energy, and trace gases change completely from summer to winter. Winter variation in energy budgets is determined by radiation inputs, whereas summer energy budgets are governed by evapotranspiration, which depends on vegetation type and governs runoff to rivers. Moisture has opposing effects on the two major trace gases: CH_4 flux declines with soil drying while CO_2 flux initially increases. This effect buffers the overall effects of the Arctic on climate forcing. Long-term effects of terrestrial ecosystems on climate depend on climatic, vegetation, and permafrost effects on soil moisture which directly regulates trace gas fluxes and indirectly determines vegetation effects on surface energy exchange. Representations of the land surface in climate models, which have been developed in the context of global models and tropical, mid-latitude and alpine regimes, are inadequate for simulations of the arctic climate system, and are likely to contribute strongly to the deficiencies observed in GCM simulations of the Arctic. These deficiencies lie in both the treatment of the soil hydrology, including permafrost, and the specification of high-latitude vegetation. Work to rectify these problems in a way compatible with GCM development is underway.

Another group of projects is integrated into the International Tundra Experiment (ITEX), an

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international collaboration with strong U.S. arctic involvement. ITEX seeks to understand the capacity of plant species and vegetation to adapt to environmental changes. This program has shown that short-term responses of plants and vegetation to manipulation are not indicative of long-term responses because of major ecosystem feedbacks that compensate for or amplify initial responses. Moreover, genetic studies indicate a strong environmental carryover (time lag) in the full response of plants to new environmental conditions. Most arctic systems are more responsive to nutrients than to temperature, suggesting that many of the temperature effects on vegetation operate indirectly through controls on nutrient cycling.

Other LAII studies treat the interaction between human communities and the response of biotic systems to climatic change. For example, social and economic factors strongly influence subsistence harvest of black brant in the Yukon-Kuskokwim Delta. Grazing by black brant, in turn, determine the morphology of a key forage species (*Carex subspathacea*) and its impact on ecosystem processes. In northeastern Alaska both climate and development have important impacts on the energetics and calving success of the Porcupine Caribou Herd. The resulting caribou population dynamics interact with a complex of social and economic processes to determine the extent of subsistence harvest of caribou from this herd. The interactions of subsistence and wage economies in turn influence the sustainability of village lifestyles in the region. These studies clearly demonstrate that human societies are an integral component of the arctic system.

An OAII Program Update: Research Findings and Priorities

Jackie M. Grebmeier[1] (Chair-OAII SSC and University of Tennessee)

The Arctic Ocean and adjacent seas are a dynamic, interactive system of water, ice, air, biota, dissolved and suspended chemicals, and sediments. The arctic system most likely affects the climatic state of the earth and responds sensitively to climate perturbations that originate outside the Arctic. The goal of the Ocean-Atmosphere-Ice Interactions (OAII) component within the ARCSS Program is to investigate interactions between the ocean, atmosphere, and ice in the arctic marine ecosystem in the context of predicting environmental change. Initial studies within the OAII Program investigated basic patterns of seasonal, regional, and interannual variability and coupling mechanisms between the arctic system and global climate change. Currently the OAII Program is evolving towards a thematic approach to scientific program development, with an increased emphasis on studies that synthesize and integrate across disciplinary boundaries as well as among different components of the ARCSS Program.

The OAII component has identified six research priority areas for scientific research to fill the gaps in our understanding of the arctic ecosystem: circulation of the Arctic Ocean, surface energy budget, atmospheric radiation and clouds, the hydrologic cycle, productivity and biogeochemical cycling, paleoceanography, and coupled modeling studies. Both large, multi-investigator programs and individual science projects are funded within the OAII Program, with over 70 individual projects having been funded to date. Four interdisciplinary, multi-year programs have been fully or partially implemented, including: the Northeast Water (NEW) Polynya project (1991–1995), the Western Arctic Marine System (WAM) program (1993–1996), the U.S./Canada Arctic Ocean Section (AOS) program (1994–1997), and Surface Heat Budget of the Arctic Ocean (SHEBA) (1995–2003: Phase I funded, Phase II initiated, followed by a proposed Phase III modeling program).

Project development within the OAII component is through a community-based process involving workshops, scientific meetings, and publication of reports and newsletters, with oversight provided by the OAII Science Steering Committee (SSC) and supported through the OAII Science Management Office (SMO). Currently the OAII research priorities include the following:

1. Surface Heat Budget of the Arctic Ocean (SHEBA): SHEBA is a coordinated project in the advanced stage of development designed to improve predictions of arctic climate by investigating the physical processes that determine the surface energy budget, sea-ice mass balance, and surface radiative properties in the Arctic Ocean;
2. Biological Initiative in the Arctic: Shelf-Basin Interactions (SBI): this initiative to investigate the physical forcing, biogeochemical transformation, and exchange of materials between the outer shelf and open Arctic Ocean is in the intermediate stages of development; a community-based workshop was held in March 1995 and development of a science plan is in progress;
3. Canada Basin Studies: an international group of arctic scientists is proposing a regional oceanographic study of the Canada

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Basin, both physical and biogeochemical, including its sensitivity to environmental forcing; and

4. The North Water Polynya (NOW) Studies: an interdisciplinary group of investigators is proposing to extend earlier polynya studies, such as NEW, in coordination with a Canadian effort to study the North Water Polynya between Baffin Island and Greenland.

Further information on the OAII Program can be obtained on the OAII Web site <http://arcss-oaii.ccpo.odu.edu>.

Human Dimensions of the Arctic

Carl Hild[1] (Rural Alaska Community Action Program)

During my first experience in the Arctic, I realized the importance of local knowledge while on assignment to investigate frostbite and hypothermia for the U.S. military. This was to be accomplished by studying wolves and polar bears as they do not suffer from these conditions. The work on wolves showed they could regulate their body temperature and therefore the heat flow from the pads of their feet—the ability to provide adequate circulation even in minus 40° liquid prevented the foot from freezing. Such study results did not provide a simple solution for the Navy in reducing the incidence of frostbite in sailors because they simply did not have the same circulation system as wolves nor the ability to regulate their blood flow. However, at the same time I was focusing my attention on wolves and polar bears, I became familiar with traditional Native health practices that had many treatments for bleeding, but none for frostbite, and only a few for hypothermia (even those were generally only for cold water situations). I later learned that Native people ate naturally fermented or raw meats and that such a diet impacts the blood composition by significantly affecting platelet aggregation. Another dietary influence was the Native practice of chewing shoots of willows—the inner bark has high levels of vitamin C and salicylic acid. Several years later Dr. William Mills, a world class expert on frostbite, recommended that Army troops in extremely cold weather take an aspirin a day to reduce the chance of frostbite. The time I spent out on the tundra and on the ocean ice with Alaska Natives taught me much about how to live and work in a cold environment. The key was not the frostbite treatment but rather prevention behavior. Now, Alaska Native customs of dealing with cold weather is recommended for those venturing into the Arctic.

This is only one example of many that emphasizes the importance of incorporating the human dimension into arctic science. Yet including Native local knowledge into arctic research will be a formidable task. Currently there is debate regarding the best methods of sharing, collecting, utilizing, and stewarding information provided by northern residents. Traditional knowledge and wisdom exist because they have enabled communities of people to survive over time. There has been no precedence for methodically considering local historical, cultural, and contemporary activities. However, an example of the changing paradigm is apparent in the formation of the Alaska Native Science Commission, the North Slope Borough's institution of a Science Tax (requiring researchers to make a presentation to the communities in which they intend to work prior to the start of their efforts), and the Marine Mammal Protection Act (which provides for Alaska Native organizations to enter into co-management agreements). The use of traditional knowledge and wisdom must be considered as should intellectual property rights and community involvement, although Native wisdom should not necessarily be measured in scientific terms.

The international community is at last calling for the involvement of indigenous peoples and their understanding of the world. In 1992, the work plan of the Human Dimensions of Global

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Environmental Change Programme was begun. The conceived linkages to a variety of other international programs, although complex, send a clear message that all research will ultimately deal with human impacts on the environment and impacts of a changing environment on humans.

The National Science Foundation, through its Arctic System Science effort, has identified an initiative on the Human Dimensions of the Arctic (HARC), which aims to incorporate, among other goals, traditional knowledge and wisdom into scientific research. HARC provides a recommendation that indigenous people be involved in the scientific process in order to assure that traditional knowledge is presented to those responsible for drafting reports and making decisions. The formalization of HARC is now underway and must be closely linked with all arctic research. HARC also provides for the concept of research teams representing diverse disciplines which is part of gaining a broader perspective on understanding the world, as well as the Arctic.

Human activities around the globe are measurable in the Arctic. The level of impact is generally unknown but there is indication that in some regions, the impact is significant. Global and local human activities influence the arctic ecosystem and its residents as revealed by a number of reports on issues such as soot on ice which affects albedo and the effect of elevated permafrost and ocean water temperatures. Global climate change can also be recognized along with Minke whale and sea otter sightings near Barrow and a river otter in Wainwright, and ice cellars in Anaktuvuk Pass that can no longer be used for year-round storage. Local residents also report the creep of willows and other bushy plants up mountainsides and further north which may affect albedo, thereby modifying local snow and ice conditions. Communities located on hunting platforms provided by ocean and freshwater ice for pursuing whales, seals, birds, and fish at various times of the year may also be jeopardized. As the ice structure and dynamics change it will clearly have a definite impact on cultural practices for these northern communities.

People have lived for millennia in the Arctic. There have always been changes. The stories of the people of the north are full of ways to deal with hardship, and the culture of the far north has forged the tools for survival in the people. We need to learn about these tools in order to better face change. We may achieve this by encouraging the diversity of cultures and by avoiding singular ways of thinking. The diversity of approaches has been the keystone to our success. Variability is not harmful—it does make scientific modeling more difficult, but it may offer strength to the resulting structure.

Models of Environmental Impact on Humans

Andrew Kerr[1](University of Edinburgh) and Tom McGovern[2]

The desire for informed judgement on the size and implications of future environmental change necessitates the incorporation of human dimensions into environmental models. This embodies both the impact of humans on the environment and the impact of the environment on social systems. It remains unclear as to the extent of the interdependence between people and their environment, both in the past and the present day. However, academic study invariably splits this problem into three components: climate, the physical environment, and the social environment. Typically, when a change is identified in one component, for example, climate, it is assumed to impact proportionately on another, for example, society; a process which ignores the myriad filters and feedbacks which lie between the two. This tendency is particularly apparent in the attempted correlation of the excellent paleoclimatic data sets with much more loosely dated or extended events occurring in a society or a physical landscape. In such cases, the description of the social or physical event is unwittingly translated into the explanation of the event by the expedience of correlating the event with well-dated climatic changes. Such work can be characterised by the statement: "It got colder so they died." (McGovern, 1991). The aim of environmental models incorporating human dimensions should be to move beyond this simple determinism and question when and why environmental changes have an impact on humans.

To model the environmental impact on humans we need to consider two points. The first is scale. Environmental change needs to be quantified on human time scales (sub-decadal measurements) and spatial scales (appropriate to a community). Currently, the GISP/GRIP records provide proxy climate data on appropriate scales, but the quality of this data depend on their regional significance. In the physical environment, the crucial data are the changes in soil, vegetation, and fauna through time.

The second point concerns the significance of history on the environment. If we wish to know the impact of a particular event on the environment then we need to know the pre-existing state of the environment, which is contingent on the climatic, social, and environmental impacts of the preceding time periods. These contingent events are the classic problem of any historical science. While some elements can be described by basic physical processes others are configurational, meaning they depend on specific events at specific times. The key to understanding such problems is the asymmetry between understanding and prediction. We can have a fairly good understanding of what happened historically, and this provides us with insight to the problem, but it does not provide us with an ability to 'predict' the future.

The questions we wish to pose of the models are those concerned with thresholds, sensitivities, and time scales of the coupled system. The models are not designed as all-encompassing truth machines, but rather as heuristic devices to explore possible outcomes of particular components of the system. Choosing the most appropriate model depends on the available data. One of the best examples of modeling the

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environmental impact on humans are the 'Farmpact' series of models (McGovern, 1995). These aim to provide a first-order sensitivity model for the Norse economy in Greenland at critical periods over the past 1,000 years, where sufficient data exist, to get a sense of the interaction between the Norse economy and the environment. It seeks to quantify the links between the climate, the physical environment, and society. Three groups of models have been developed: models based on the impact of climatic change on pasture productivity, models of possible human responses to environmental change, and reference and 'what if?' models, based on present day data, used to examine linkages between system components. Three periods are characterized: good times, hard times, and catastrophe; and reflect possible responses of the physical environment to climatic and human pressures, and the consequent impact of the environment on humans. The strengths of such modeling work derive from the comprehensive studies of North Atlantic agricultural systems which have been undertaken, the quantifiable linkages between components of the model, and the formulation of testable ideas. Its weaknesses reflect its over-simplified and static nature and the lack of a geographical component.

In summary, models of environmental impacts on human society are currently being developed for the North Atlantic region. The key to such models is the need for data on scales appropriate to human temporal and spatial scales, and the importance of historical contingencies on the evolution of the physical and social landscapes. These models provide insight to the nature of the interdependence of humans and the environment.

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ARCSS SIMS and Modeling

Amanda Lynch[1] (University of Colorado-Boulder)

The aim of the Synthesis, Integration, and Modeling (SIMS) initiative of the Arctic System Science (ARCSS) Program is to take a multi-disciplinary approach to the role of the Arctic in the climate system to achieve a comprehensive synthesis of understanding regarding arctic systems. The key to this approach is collaboration, across disciplinary boundaries and between ARCSS components (LAII, OAII, PALE, GISP2, and HARC).

Modeling can be understood as an integration of all known information about a system. Hence, modeling is one useful tool to realize this integration of approaches and synthesis of understanding. Within the SIMS initiative, then, it is important to achieve collaboration, not only among modelers, but between investigators involved in modeling and those involved in theoretical work and data acquisition. The Modeling Working Group has identified the following structure for current modeling efforts within the ARCSS Program (Figure 1).

Obviously some aspects of modeling with the various components of ARCSS are more mature than others. For example, the projects within the HARC component are still very new, and full use of tools such as integrated assessment models is still in the future. However, since integration amongst the various projects need not involve the actual coupling of models, this is not a barrier to collaboration between the modeling efforts in the various components.

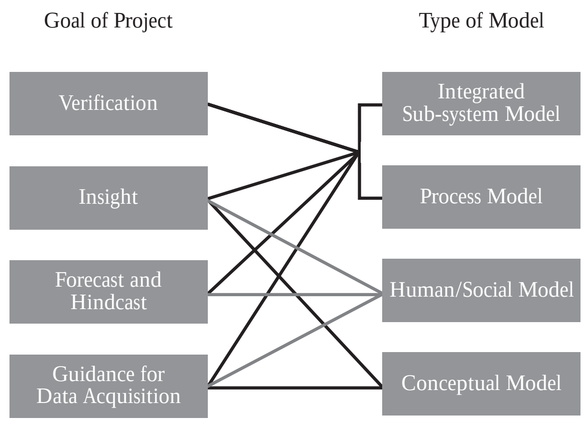

Figure 1. Structure of current modeling efforts within the ARCSS Program.

Integration of current and future ARCSS modeling projects can take two forms:

- collaboration among modelers, and
- collaboration between modelers and non-modelers.

The former can include the coupling of one component to another; the coupling of one scale to another (*e.g.*, nesting); the integration of information from various regions in the Arctic; and conceptual linking, such as using climate-change scenario predictions as guidance for a human/social model. The latter includes integrated approaches which use multiple forms of data in concert with specifically targeted model experiments; using models in concert with specifically targeted field programs, and conceptual linking, such as the use of historical and archaeological data as verification for paleoclimatic model reconstructions. Thus, in the context of SIMS, the new structure for modeling within the ARCSS Program should be (Figure 2, next page):

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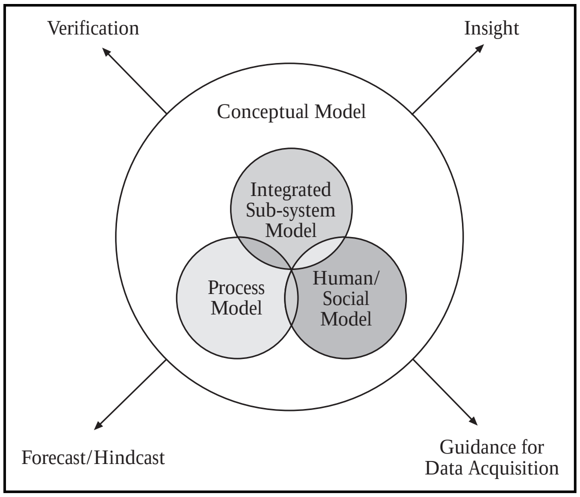

Figure 2. Proposed structure of future modeling efforts within the ARCSS Program, in the context of SIMS.

In order for this integration to take place, the issues of data and model output availability must be addressed, as well as the possibility of availability of the models themselves. In summary, synthesis and integration requires efficient sharing of information about current and planned ARCSS projects, collaboration both in the design of projects and their execution, and the crossing of disciplinary boundaries.

Major Features and Forcing of High Latitude Northern Hemisphere Atmospheric Circulation Over the Last 110,000 Years

Paul A. Mayewski[1] (University of New Hampshire), Loren D. Meeker,[2] Mark S. Twickler,[3] and Sallie I. Whitlow[4]

The GISP2 Ice Core

Ice cores recovered from Summit Greenland have provided a new view of climate change that is based not only on classic temperature reconstructions (developed through stable isotope measurements) but also on the reconstruction of changes in atmospheric circulation pathways and intensity. Such reconstructions (Mayewski *et al.*, 1993, 1994, 1997) can now be developed through the identification of chemical "signatures" in ice cores (unique assemblages of the chemical components (calcium, magnesium, potassium, sodium, ammonium, chloride, sulfate, and nitrate) that comprise >95% of the soluble chemistry in the atmosphere).

Atmospheric Circulation During the Last Ice Age

Bandpass components (Figure 1; Mayewski *et al.*, 1997) developed from highly significant frequencies found in the high-resolution time series of these chemical species reveal that long-term (millennial scale and greater) change in atmospheric circulation is controlled largely by the insolation changes related to Earth orbit cycles and by changes in ice-sheet dynamics (triggered by the lag between insolation driven ice volume change and insolation) as previously described from the marine sediment record. However, faster changes in atmospheric circulation, that turn on and off in a decade or less, shed new light on our concept of climate change. These so-called rapid climate change events (operating at periods of 2200, 1450, and 510 years) appear to be related to some combination of ocean, atmosphere, sea-ice, or solar intensity variability.

Atmospheric Circulation During the Last 11,500 Years

Climate events, in general, appear magnified when ice sheets covered the mid-high latitudes of the Northern Hemisphere. However, subdued versions of events such as the rapid climate change events have now been identified in the Holocene (Figure 2; O'Brien *et al.*, 1996). Both the timing and relative magnitude of these events appear to be well-correlated to changes in solar intensity (based on the $\partial^{14}C$ residual series from tree rings) plus other climate forcings such as changes in insolation and volcanic aerosols.

Little Ice Age-Style Atmospheric Circulation Patterns Continue Today

The most recent of the changes in atmospheric circulation that characterize the Holocene rapid climate change events and the event with the most dramatic onset is the Little Ice Age (onset approximately AD1400–1420) (Mayewski *et al.*, 1993, O'Brien and Mayewski *et al.*, 1995). Considerable decadal- and finer-scale variability

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in atmospheric circulation characterizes the Little Ice Age. Modern atmospheric circulation, as interpreted from our records, appears to still be within the range of variability of the Little Ice Age.

Predictions of future climate change may be significantly improved by considering climate in terms of not only a greenhouse gas-warmed and sulfate aerosol-cooled Earth but also in terms of natural change in atmospheric circulation.

For further information about this work, see:

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The Rapidly Changing Arctic Environment: a Paleoenvironmental Perspective

Jonathan T. Overpeck[1] (NOAA Paleoclimatology Program and INSTAAR), a product of the PALE High-Resolution Working Group[2]

A major new contribution of PALE has been the development of annually dated paleoenvironmental time series from lake sediments, thus providing the opportunity to bridge tree-ring-derived records from tree-line and the sparse coverage of more northerly important ice-core records. The lake-sediment records also allow multiple proxy records of past climate change to be intercompared, and thus checked against each other to make sure they are faithfully recording past environmental change in all frequency bands. For example, tree-ring, ice-core, and lake-sediment records from the eastern Canadian Arctic all show the same basic pattern of decade-to-century-scale change over the last 400 years.

Our compilation of approximately 25 new and previously published time series from lakes, trees, glaciers, historical records, and marine sediments provides the first multi-proxy view of circumarctic environmental variability of the last 1,200 years. Mid-20th century arctic summers were, in general, the warmest of the last 400 years, but not the last 1,200 years. The period 1850 to 1940 witnessed the only major circumarctic summer temperature shift of the last millenium. This dramatic warming, and resulting impacts on the terrestrial biosphere, lakes, and glaciers, represented the end of the arctic "Little Ice Age" that began asynchronously before 1600. Although some amount of the warming after 1920 was likely due to anthropogenic increases in atmospheric trace gases, the initiation of the warming in the mid-19th century suggests that natural forcing played a role. Comparison of the reconstructed climate with hypothesized solar forcing shows some similarity, but also some significant disagreement. Volcanic forcing appears likely for interannual-to-decade-scale variability. Little evidence for North Atlantic heat transport forcing can be observed, but a complete test of this hypothesis must await inclusion of data from outside the Arctic.

Our compilation supports the previously made assertions that Norse settlers on Greenland were forced by cold/short summers to abandon their settlements in the 14th and 15th centuries. Our compilation also makes it clear that the cold 19th century was a poor time for Europeans to have been searching vainly for the Northwest Passage. Significant climatic, oceanographic, vegetational, limnological, and glacialogical change, rather than stability, is the norm for the Arctic.

For further information about this work, see:

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The Color of Global Change: Environmental Variability in the Polar Regions

Warwick F. Vincent[1] (Laval University)

Is there really global warming or the cyclical variations of the weather observed by the elders and passed down for the knowledge of the next generation? (Mr. Peter Ernerk of Rankin Inlet, northern Canada).

Environmental variability has always been of special concern to indigenous people living in the north polar region, particularly through its effects on food availability. The extent and duration of sea-ice cover, for example, and the access to open water, strongly influence the timing and success of traditional hunting and fishing activities (Freeman, 1994). A variety of climate change scenarios have been proposed for different parts of the Canadian Arctic ranging from increased growth of tundra plants to feedback effects resulting in prolonged snow cover. These disparate predictions in combination with the large east-west differences in warming trends—for example, the Eastern Canadian Climate Anomaly of recent cooling in northeast Canada and Greenland (Ernerk, 1994)—have generated confusion and skepticism among arctic residents about the nature and potential impacts of global change.

The remarkable nature of water and in particular the large, abrupt changes in its physical properties across the freezing point have a major effect on the structure and variability of polar environments. For many parts of the Arctic, subarctic, and the coastal regions of Antarctica there is a precarious balance between freezing and melting through much of the growing season. These effects translate into an enhanced sensitivity to small variations in climate and can give rise to large interannual variations in many of the biological characteristics of marine, freshwater, and terrestrial ecosystems.

Color is an integrative measure of a variety of ecosystem gain and loss processes that is of interest to consider in the context of global change, particularly since any effect on the upwelling spectral irradiance field has the potential to be measured remotely, for example, by satellite. There is some evidence from Antarctica of increased colonization and seedling recruitment of two species of higher plants (*Colobanthus quitensis* and *Deschampsia antarctica*) in response to current warming trends (Lewis-Smith, 1994). As noted by Josef Svoboda (Svoboda, 1994), however, the optimistic prospect for northern, high-latitude regions, that if the climate keeps its warming trend a prosperous era of a green land will set its course, needs to be counterbalanced by uncertainties regarding cloud and precipitation effects, for example, that the expected increase in winter precipitation might shift the direction of climate change towards neoglaciation and an increased duration of whiteness in the polar landscape.

Color is of special interest to limnologists, who use the term water color to refer to the natural staining of lakes and rivers by chromophoric dissolved organic matter (CDOM). This material, also referred to as gelbstoff, gilvin, or yellow substances, is largely composed of humic and fulvic acids derived from vegetation in the surrounding catchment. Our transect analyses from the subarctic to high arctic show that there is a marked decrease in CDOM concentrations in lakes across the ecotonal gradient from boreal forest to tundra (Vincent and Pienitz, 1996), and a further decline across the transition to polar desert (Vincent, 1997). This yellow coloration controls not only the underwater attenuation of photosynthetically active radiation (PAR) but also

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of ultraviolet radiation (UVR) and the spectral ratio of UVR:PAR (Laurion *et al*., 1997). This latter ratio appears to play a critical role in the balance between photochemical damage to aquatic biota and their recovery via light-activated repair mechanisms.

Climate change is likely to strongly influence the export of UV-screening CDOM into lakes via effects on hydrology and terrestrial carbon cycling. Historical variations in the UV optical properties of Northern lakes is now under investigation by paleolimnological studies to hindcast CDOM from fossil diatom records contained within the sediments (Pienitz and Smol, 1993) and by development of CDOM-UVR spectral models (Laurion *et al*., 1997). These paleo-optical studies should allow current trends in the changing underwater spectral regime of polar and subpolar lakes to be placed in the context of their long-term variability.

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Changes in the Arctic System

John E. Walsh[1] (University of Illinois)

The planning and early implementation phases of ARCSS have entrained a wide variety of scientists into a regional program that has the potential to be a prototype for global system science. In order to fulfill its potential and leave an exemplary legacy, ARCSS needs to make substantive progress with respect to (1) understanding of feedbacks in the system, (2) the scaling of processes in the system, and (3) the anticipation of surprises in the system's future behavior.

With regard to feedbacks, the arctic system contains a sufficient number of components that the interactions are numerous and complex. Even within individual components of the arctic system, many feedbacks are poorly understood. For example, the sign of the feedback between changes in cloudiness and annual mean surface temperature is not known because clouds appear to warm the surface during the winter months and cool the surface during the summer months. There is clearly a need to quantify the feedbacks that are mentioned so often in the ARCSS planning documents. Quantification will be a daunting challenge when the feedbacks involve (as they generally do) more than one component of the arctic system (*e.g.*, atmosphere, ocean, ice, land surface, vegetation, humans).

Scaling strategies and algorithms are required in order to extrapolate local ("point") measurements to the regional scale. The LAII Flux Study and SHEBA are examples of ARCSS-coordinated projects for which success will require innovative and scientifically sound procedures for scaling. Successful scaling will not only permit regional budget studies, but it will provide a basis for the verification of models and for the development of improved parameterizations in models. Key tools for scaling in ARCSS are satellite remote sensing and a variety of models, ranging from conceptual to empirical to physically based. An immediate need is the quantification of the uncertainties in present scaling algorithms and model parameterizations. The largest uncertainties can serve to guide field programs in ARCSS. Additionally, there is a need for a system model within ARCSS in order to identify the system interactions for which improved scaling is most essential, thereby providing some cross-disciplinary priority setting within ARCSS.

Finally, ARCSS will provide a high return on the scientific and funding investments if it leads to the anticipation of environmental changes that might otherwise occur as "surprises." Future changes may go against the grain of what is now the "conventional wisdom." For example, amid the pervasive concern about global warming due to greenhouse gases, northeastern Canada and the western North Atlantic have exhibited a cooling during the past several decades. Northeastern Canada is presently snow-free for only short periods during the summer, and the area is underlain by permafrost. Since precipitation is now increasing over much of the northern high latitudes, the region may be delicately poised with respect to a neoglaciation (Svoboda, 1995). Interestingly, analyses of the GISP2 ice core in ARCSS indicate that snow accumulation at the Greenland summit has increased substantially during periods of warming. A challenge to ARCSS is to ensure that future changes in this and other high-latitude areas are not "surprises" but are anticipated by planners and policy makers.

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Integrated, Interdisciplinary Approaches to Understanding the Arctic System: Environment, Resources, and People

Patrick J. Webber[1] (Michigan State University)

As a former ARCSS (Arctic System Science) Program Director permit me to echo the admonition from the present Director, Dr. Michael Ledbetter, that ARCSS research concerns the arctic system and currently focuses on Global Change. At this meeting and as we continue to do ARCSS research we must be continually mindful of these attributes. In this presentation I will emphasize expanding the dimensions of the present suite of ARCSS projects to meet these criteria. ARCSS concerns understanding the dynamics of the Arctic as a single subsystem of the earth system. As such we should favor the holistic approach to understanding over the reductionistic approach. In other words we must increase the scale of our observation and be more integrative. Further we must go beyond the almost singular focus of the Program on climate change to include other changing states and drivers of the arctic system, such as land development, environmental pollution, and resource harvesting. The focus on climate change, while important, should not lead us to neglect other agents of change which are quite possibly more direct and immediate than climate change and which also interact with climate. It is my view that ARCSS has, to date, mirrored the activities of the IGBP (International Geosphere Biosphere Programme) and the USGCRP (United States Global Change Research Program) in which climate change and physical and chemical aspects of the earth system have received most attention. Research plans of these programs have always included other elements of the global system, such as humans and the biota, but these foci get short shrift. This latter shortfall reminds me of a saying which is usually attributed to Mahatma Ghandi:

There are seven things that will destroy us:

Wealth without work
Pleasure without conscience
Knowledge without character
Business without ethics
Religion without sacrifice
Politics without principle
Science without humanity

Mohandas Ghandi

While I should not over-interpret Ghandi's intent I believe that ARCSS as science must not ignore the human dimension and it should seek to improve the human condition. Further, in the context of ARCSS and with the greatest of respect for the Mahatma, I would add to the last line of the quote the words "and a concern for living things," that is, the biota. Ghandi was no doubt also mindful of the power of discovery to do harm as well as good and as we enter the realm of social science I remind you to abide by the *Principles for the Conduct of Research in the Arctic* as stated by IARPC in 1990.

ARCSS is a vibrant program which, to the credit of its originators and investigators, has already made some notable discoveries (for example: very abrupt arctic climate changes, R.B. Alley, this report; recent Arctic Ocean warming, K. Aagaard, this report; and carbon source/sink changes in the terrestrial ecosystem [Oechel *et al.*, 1993]). Nevertheless for ARCSS to reach its stated goals (*Arctic System Science: A Plan for Integration*), it must change its research balance to embrace more completely the continua shown in Figure 1, next page. By including the segments of the continua towards the right hand side of the diagram, ARCSS becomes more holistic and increases its biotic and human dimensions. Moving to the right along these

continued on next page

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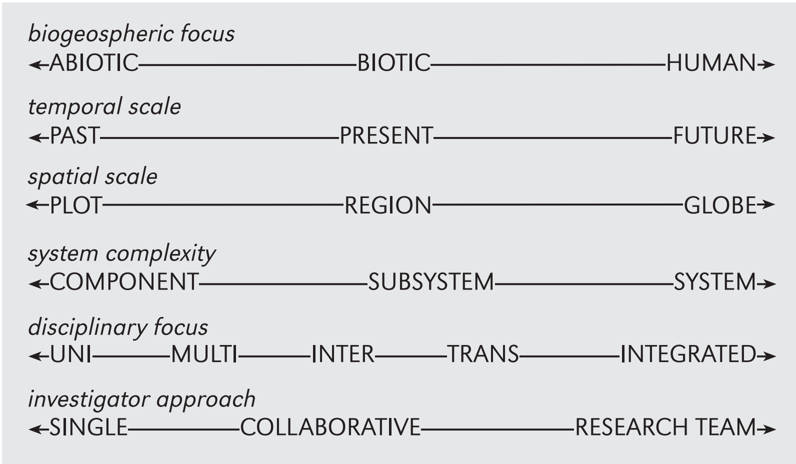

Figure 1. For ARCSS to reach its stated goals, it must change its research balance to embrace more completely the continua shown here. By including the segments of the continua towards the right hand side of the diagram, ARCSS becomes more holistic and increases its biotic and human dimensions. Moving to the right along these continua increases scales of observation, subsystem complexity, difficulty of prediction, and need for interdisciplinary team work.

continua increases scales of observation, subsystem complexity, difficulty of prediction, and need for interdisciplinary team work. The processes and techniques called synthesis, integration, and modeling become the means to meeting the challenge presented by such a move. The emerging SIMS (Synthesis, Integration, and Modeling Studies) component of the ARCSS Program offers promise in helping with this challenge but it does need clear articulation and development (see A. Lynch, this report); I commend the SIMS concept to you and ask that you help develop it.

As you consider your own progress and future directions for ARCSS I urge you to include contemporary studies, human dimensions, and renewable resources as important elements of your research. To change the balance of research in ARCSS and to increase synthesis and integration creates, because of finite funding resources, a challenge which forces tradeoffs, reallocation, and postponement of research. Please consider this a challenge during this workshop.

Finally, I wish to point out a special attribute of the ARCSS Program that has a bearing on the future of arctic system science and the issue of broadening its research portfolio to go beyond climate change and to address issues more proximal to the real world. ARCSS is unique among the NSF (National Science Foundation) contributions to the USGCRP because it is a formal Program in the structure of NSF. In particular it is a formal Program in the Arctic Section of the NSF Office of Polar Programs. No other NSF Global Change project has Program status with a capital P. Further, most other Global Change programs (note lower case p) are almost exclusively focused on climate and as such if funding for climate change research diminishes they will be scaled down and quite possibly discontinued since they are only research initiatives within a Program and not programs in their own right. However, ARCSS by virtue of being a Program with a mandate broader than climate or even global change has a greater permanency and can thus compete for funding for other initiatives. This is important for the future of the arctic system.

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Crossing the Intellectual Divide: Studying the Links between Biophysical and Human Systems

Oran R. Young[1] (Dartmouth College)

Building balanced and mutually rewarding partnerships between the natural sciences and the social sciences in an ARCSS setting is both a necessity and a stimulating challenge. Success in this endeavor will require the development of an integrated research agenda that identifies topics of interest to leading members of both communities and the deployment of a set of programmatic strategies to strengthen the incentives of natural scientists and social scientists to work together on such topics.

Among those topics that seem appropriate for inclusion on an integrated research agenda are:

1. biophysical responses to social drivers including variability, thresholds, nonlinear response patterns, surprises, and scale effects,
2. social responses to biophysical drivers including types of response, such as adaptation vs. mitigation,
3. interactions among anthropogenic and biophysical drivers (*e.g.*, human harvesting and changes in water temperatures in large marine ecosystems), and
4. interaction effects and feedback loops (*e.g.*, the cascade hypothesis regarding the dynamics of the Bering Sea ecosystem).

Programmatic strategies that will help to encourage the development of effective partnerships include:

1. the organization of science planning exercises at national and international levels,
2. an emphasis on problem-driven or thematic research (*e.g.*, understanding the dynamics of the Bering Sea as a large marine ecosystem),
3. offering both material and intellectual rewards for scientists who form effective partnerships linking the natural sciences and the social sciences, and
4. a willingness to take risks in supporting holistic (in contrast to reductionistic) approaches to the study of complex, coupled systems.

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Surface Turbulent Fluxes over Leads in the Arctic

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Leads are quasi-rectilinear cracks in the sea ice resulting from dynamic motions within the ice pack. The occurrence of open water areas in the sea ice is of major significance for the ocean-atmosphere exchange of heat and moisture, particularly during winter, when air-sea temperature differences may be 20–40° C over leads. Leads are thus essential elements in any study of the Arctic Ocean heat budget. We present a new turbulent flux model to compute heat and momentum fluxes over leads in the arctic sea ice. The momentum roughness length uses a sea-state parameterization which is fully consistent with the surface-turbulent flux parameterization. The flux parameterization accounts for the fetch dependence, which is a significant variable in the lead problem as the airflow over a lead is typically limited by fetch. The surface roughness length for heat is determined from an application of surface renewal theory to the air-sea interface. The fluxes are compared with in situ observations of lead fluxes. We have also compared our model results with a bulk flux algorithm which has been commonly used to evaluate surface-heat fluxes from leads. We have computed integral heat fluxes as a function of lead width for various atmospheric states in the Arctic to assess heat flux in a mesoscale model grid in which a lead is present.

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For further information about this work, see:

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Temporal and Spatial Variations in Late Quaternary Vegetation of Northeastern Siberia

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PALE research has focused on four regions of northeastern Siberia: northern Chukotka-Wrangel Island, southern Chukotka, the Upper Kolyma drainage, and the northern Okhotsk sea coast. Modern climates and vegetation types, geomorphology, and glacial histories differ in each area, thereby providing a means for assessing the range of responses to climatic fluctuations over the last glacial-interglacial cycle. Pollen analyses of lake sediments yield continuous records of variations in the composition and distribution of plant communities and indicate that the late Quaternary vegetation history of far northeastern Asia is more complex than previously thought. Examples of temporal-spatial variations include:

1) *Larix* forest established earlier in interior than coastal areas;
2) *Pinus pumila* establishes prior to *Larix* in southern coastal areas;
3) *Pinus pumila* populations fluctuated in some coastal areas during the Holocene; and
4) the composition of the dominant pollen taxa in full-glacial tundra communities from the Okhotsk sites differs from other sites.

Comparisons to the Alaskan pollen records suggest that the composition of plant communities and times of vegetation change differed across Beringia. In particular, the post-glacial establishment of coniferous forests occurs earlier in northeastern Siberia and, in contrast to Alaska, is not preceded by a period of *Populus* dominance. Such paleovegetational patterns imply strong regional responses to changes in global climatic conditions of the last 20,000 years.

For further information about this work, see:

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Do General Circulation Models Underestimate the Natural Variability in the Arctic Climate?

D.S. Battisti [1] (University of Washington), C.M. Bitz,[2] and R.E. Moritz[3]

Modeling studies to ascertain the effects on the climate system of increasing greenhouse gases in the atmosphere indicate that the climate change may be most significant in the Arctic because of feedbacks associated with the sea ice. Unfortunately, the natural variability in the polar regions of these models has not been fully documented. Furthermore, the veracity of the simulated arctic climate can not be evaluated rigorously because there are insufficient observations of the time history of the state of the arctic climate system. In this paper we examine the natural variability of the arctic climate system simulated by two very different models: the Geophysical Fluid Dynamics Laboratory (GFDL) global climate model, and a model of the arctic atmosphere/sea-ice/upper-ocean system averaged over the polar cap: the PCCM. The area-averaged, sea-ice thickness is taken to be a proxy for the state of the arctic climate system because it is the slow component of the arctic climate system (compared to the atmosphere); it may contribute to the variability in the freshwater storage (important for the thermohaline circulation), and it is crucial for the partitioning of energy between the ocean and atmosphere. A 1,000-year integration of the regionally averaged arctic climate model is performed in which the model is driven by a prescribed, stochastic atmospheric energy flux convergence (D) which has spectral characteristics that are identical to the spectra of the observed D. The standard deviation of the monthly mean sea-ice thickness from this model is 0.86 m; the mean sea-ice thickness is 3.1 m. In contrast, the standard deviation of the monthly averaged sea-ice thickness in the GFDL climate model is found to be about 5% of the climatological mean thickness and only 21% of that simulated by the PCCM. We present a series of experiments to determine the cause of these disparate results. First, after changing the treatment of sea-ice and snow albedo in the (standard) PCCM model to be identical thermodynamically to that in the GFDL model, we drive the PCCM with D from the GFDL control integration and demonstrate that the PCCM model produces an arctic climate similar to that of the GFDL model. We then examine integrations of the PCCM in which the different prescriptions of the sea-ice treatment (GFDL vs. standard PCCM) and D (GFDL vs. observed) are permutated. Our results indicate that unarguable improvements in the treatment of sea ice in the GFDL climate model should amplify significantly the natural variability in this model. We present calculations that indicate the variability in the sea-ice thickness is extremely sensitive to the spectrum of the atmospheric energy flux convergence. Specifically, the differences between the GFDL and observed D at time scales shorter than three years are shown to have a significant, deleterious impact on the sea-ice variability on all time scales. A best estimate for the amplitude of the natural variability in the arctic sea-ice volume is presented; this estimate is a significant fraction (about 20%) of the mean sea-ice thickness. Our results suggest that most of the global climate models that have been used to evaluate climate change may also have artificially quiescent natural variability in the Arctic. Because of the strong nonlinearity and long time scales of variability inherent to the Arctic (due to sea ice), our results raise concerns about the veracity of the climate change predictions for the Arctic from these models.

For further information about this work, see:

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Changing Origin of Ice Rafted Clastic Debris for the Northwind Ridge, Western Arctic Ocean, During the Late Pleistocene-Holocene Transition

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Glacial icebergs from the southwestern Canadian Arctic Islands drifted westward to the Northwind Ridge area during the late stages of Laurentide ice recession, while the Holocene period was dominated by sea-ice rafting from northern Alaskan sources. Box core BC 6 from the Northwind Ridge, western Arctic Ocean, shows what appears to be the Late Pleistocene-Holocene transition with an upper, fine-grained unit with abundant foraminifera and low quantities of ice-rafted erratic rock and mineral fragments (dropstones), and a coarse-grained layer with few foraminifera and abundant dropstones underneath. The Late Pleistocene-Holocene boundary in 25 cm depth is expressed as a drop in >250 fm weight percentages from 2–12% in the lower unit to less than 0.5% above. The same boundary was also observed in box core BC 17 from a nearby location and was C-14 AMS dated to be 8,500 years old. At this boundary, the major sources of ice-rafted debris shifted from an area formed by Banks, Victoria, Melville, and Bathurst Islands in the southwestern Canadian Arctic Archipelago to the northern coast of Alaska. The source areas were determined by statistical comparison of the core material with samples from suspected source regions in the North American Arctic, Greenland, Svalbard, and the Kara Sea, using two independent data sets: (1) dropstone composition data (>250 fm fraction), obtained with optical microscopy (one analysis per sample), and (2) Fe-oxide, single-grain geochemistry data measured with an electron microprobe (multiple analyses per sample).

For further information about this work, see:

Bischof, J., D.L. Clark, and J.S. Vincent. 1996. Origin of ice-rafted debris—Pleistocene paleoceanography in the western Arctic Ocean. *Paleoceanography* 11 (6): 743–756.

Darby, D.A., J.F. Bischof, and G.A. Jones. 1997. Radiocarbon chronology of depositional regimes in the western Arctic Ocean. *Deep-Sea Research II* 44 (8): 1745–1757.

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Arctic Landscape Flux Survey (ALFS) Airborne Measurements of Carbon Dioxide and Energy Fluxes Over the North Slope— 1994, 1995

Steven Brooks[1] (NOAA/Atmospheric Turbulence and Diffusion Division), Timothy Crawford,[2] and Robert McMillan[3]

During the summer months of 1994 and 1995, NOAA's Atmospheric Turbulence and Diffusion Division, in conjunction with San Diego State University, measured flux densities of mass, momentum, and energy from an airplane along one latitudinal and one longitudinal transect on the North Slope of Alaska. The experiment consisted of over 100 flights, occurring over a range of weather conditions during both daytime and evening hours. This presentation describes the surface/atmosphere exchanges of carbon dioxide and energy fluxes as observed along the transects. Overall, the east-west and north-south transect CO_2 fluxes show uniformity throughout the coastal plain despite north-south gradients in temperatures and vegetation NDVI. In addition, the east-west transect results are similar to the north-south transect results at the crossing latitude (69°54'). Significant daytime sources are the major rivers (Sagavanirktok and Colville) crossed by the east-west transect. This is a clear example where the aircraft measurements have been particularly successful in resolving landscape-level patterns of flux. The overall uniformity and similarities between 1994 to 1995 flux measurements makes extrapolation to the circumpolar Arctic a possibility. The oil-production-facility, carbon-dioxide emissions plumes were studied with the flux aircraft in August of 1995. Large carbon-dioxide plumes with concentrations of 45 ppm above ambient levels were measured 15 km downwind of the Prudhoe Bay, Alaska, major oil production facilities. The measured oil field emissions were 1.3 million kg (C) per hour.

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Late Quaternary Vegetation and Climate of the Central Arctic Foothills, Alaska

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Ahaliorak Lake (68°55' N, 151°20' W), located in the central Arctic Foothills, was cored as part of a project to study the vegetation and climate history of the Alaskan North Slope for the 0–20,000 and the 0–150,000 time intervals of PALE. Present vegetation cover is tussock shrub tundra, dominated by *Eriophorum vaginatum*, *Betula glandulosa/Betula nana*, and a variety of ericaceous shrubs (*e.g.*, *Vaccinium* spp., *Ledum* spp., *Arctostaphylos* spp.). Prominent fluctuations in herb, shrub, and tree pollen in the Ahaliorak record indicate two distinct warm and cold intervals, indicating that the core encompasses two glacial-interglacial cycles. Vegetation during both cold periods, assigned Illinoian and Wisconsinan equivalent ages, was likely a sparse herb tundra with *Salix* shrubs restricted to streamsides and moist depressions. Pollen assemblages suggest that climatic conditions were more severe during Illinoian than Wisconsinan times and that the most extreme conditions occurred during the terminal phases of each glaciation. Unlike the cold periods, vegetation differed between the warm intervals of the Holocene and Sangamon (*sensulato*). Shrub tundra characterizes the Holocene vegetation, whereas *Picea* forests dominate during Sangamon times. In the latter period, *Picea* pollen reaches values similar to those (>20%) currently found in continuous boreal forests of central Alaska, indicating the presence of closed coniferous forests on the North Slope. The northward extension of boreal forest in Alaska is strong evidence that the Sangamon was substantially warmer than present at northern high latitudes.

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Buoyancy Equilibration Produced by Shallow Convection in an Idealized Coastal Polynya

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The recent theoretical approach of Visbeck, Marshall, and Jones (1996) is used to examine shallow convection and offshore transport of dense water from an idealized coastal polynya. A constant negative buoyancy flux is applied in a half-elliptical region adjacent to a coastal boundary, initially causing a linear increase in density with time beneath the forcing. A baroclinically unstable front forms at the edge of the forcing region. The width of the front is imposed by the distance over which the buoyancy forcing vanishes offshore, provided this distance is larger than the baroclinic Rossby radius. Baroclinic eddies develop along the front and exchange dense water from the forcing region with ambient water, eventually reaching an equilibrium in which the lateral buoyancy flux by eddies balances the prescribed surface buoyancy flux. The time to reach equilibrium t_e and the equilibrium density anomaly r_e are given by:

$$t\_e=\beta\left(\frac{f\,W\,b}{B\_0}\right)^{1/2};\quad r\_e = \beta\left(\frac{r\_0}{gH}\right)(f\,B\_0\,W\,b)^{1/2}$$ where

B_0 is the imposed buoyancy flux, b the offshore width of the forcing region, W the distance over which the forcing vanishes, H the water depth, f the Coriolis parameter, r_0 a reference density, and g gravitational acceleration. Finally,

$$\beta = \left[\frac{\pi}{2c'\,E}\left(1-\frac{b^2}{a^2}\right)\right]^{1/2}$$ where a is the length of the forcing region along the coast, c' is the efficiency of eddy exchange, and E is the complete elliptic integral of the second kind. These parameter dependencies are fundamentally different from previous results for deep or shallow convection (1/2 power rather than 1/3 or 2/3) owing to the influence of the length scale W. The scalings are confirmed with numerical calculations using a primitive equation model. Eddy exchange in shallow convection is several times more efficient than in open-ocean deep convection. Some implications for arctic coastal polynyas are discussed.

For further information about this work, see:

Chapman, D.C., and G. Gawarkiewicz. 1997. Shallow convection and buoyancy equilibration in an idealized coastal polynya. *Journal of Physical Oceanography* 27 (4): 555–566.

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Late Cenozoic Sr Isotope Evolution of the Arctic Ocean: Constraints on Water Mass Circulation with the Lower Latitude Oceans

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Direct measurements of the Sr isotope composition of the different water masses that comprise the chemically and thermally stratified modern Arctic Ocean yield $^{87}Sr/^{86}Sr$ ratios that are homogeneous and identical (*i.e.*, within an error of $1x10^{-5}$) to the $^{87}Sr/^{86}Sr$ ratios of the lower latitude oceans. Variations in the $^{87}Sr/^{86}Sr$ ratios of planktonic foraminifera from the Arctic Ocean, which define the Sr isotope composition of shallow arctic seawater, follow the Sr isotope variations of the lower latitude oceans over the past 0.9 m.y. These new Sr isotope data support the chronostratigraphy that has been previously established for the Pleistocene Arctic Ocean. Moreover, the results indicate that although the Arctic Ocean is nearly an enclosed basin and river runoff constitutes a significant portion of the modern surface waters, the Arctic Ocean has been in Sr isotope equilibrium with the world ocean throughout most of the Pleistocene. This conclusion is clearly supported by data for samples younger than 0.9 Ma, and is considered to be consistent with the Sr isotope compositions of samples that are as old as 1.6 Ma. The Arctic Ocean has thus probably strongly affected global climate via water mass exchange since 0.9 Ma, and probably since at least 1.6 Ma.

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For further information about this work, see:

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Animal-Sediment Interactions in the Northeast Water Polynya (NEWP) and the Arctic Ocean Basin

Lisa M. Clough[1] (East Carolina University), Will G. Ambrose, Jr.,[2] and J. Kirk Cochran[3]

We present our view of the Arctic Ocean from the perspective of the benthos:

1) in a relatively small, shallow (<400 m) polynya region located off the northeast coast of Greenland (NEWP), and
2) along a transect across the entire Arctic Ocean basin (AOS).

For the NEWP region macrobenthos abundance and activity appeared to be correlated with sedimentary pigment concentrations. This tight coupling of benthic and pelagic processes was not observed in regions adjacent to the polynya which are only sporadically ice-free, nor was it observed in the ice-covered, deep (1000–2400 m) Arctic Ocean basin. Instead, macrofaunal activity and biomass appeared to be related to both water depth, and to the hydrography of the region, possibly because benthic pigment concentration was always >5 ng/ml. However, benthic biomass and activity was significantly higher than previously reported for the high Arctic, perhaps because previous work has focused on the relatively more oligotrophic waters beneath the Beaufort gyre. We conclude that benthic parameters on the arctic shelves are primarily influenced by the direct rain of food from waters above, while the deeper basins in the Arctic seem to respond primarily to hydrographic patterns.

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For further information about this work, see:

Clough, L.M., W.G. Ambrose, Jr., C.J. Ashjian, D. Piepenburg, P.E. Renaud, and S.L. Smith. 1997. Meroplankton abundance in the Northeast Water Polynya—insights from oceanographic parameters and benthic abundance patterns. *Journal of Marine Systems* 10 (1–4): 343–357.

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Radionuclide Burdens in Sediments Entrained in Arctic Ocean Sea Ice: Progress Report

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Collections of sea-ice-entrained sediments by U.S. Army Cold Regions Research and Engineering Laboratory staff that were made during the U.S.-Canada Arctic Ocean Section in 1994 showed higher than expected ^{137}Cs activities (up to 73 Bq kg-1 dw). These activities are roughly an order of magnitude higher than observed in arctic continental shelf surface sediments. We have been conducting additional analyses of the sea-ice-entrained sediments to identify the sources or mechanisms that lead to the higher than expected ^{137}Cs activities. Plutonium isotope analyses show that most of these sea-ice-entrained sediments contain plutonium that is consistent with bomb fallout origin. These ^{240}Pu:^{239}Pu ratios in the sea-ice-entrained sediments are significantly higher than deep-water benthic sediments collected during the U.S.-Canada Arctic Ocean Section, which indicates that sea-ice entrainment of sediment cannot be important on decadal scales for transport of plutonium to deeper arctic basins. The sea-ice sediment sample with the highest ^{137}Cs and the highest total plutonium activity had a ^{240}Pu:^{239}Pu ratio of 0.171, only slightly below bomb fallout, but similar to Ob River delta sediments. Nevertheless, C/N ratios in organic material associated with this sample were low (7.5 w/w) and ∂^{13}C values associated with the organic material were high (–20.5%), contraindicating an estuarine origin. Samples with high (terrestrial) C/N ratios (up to 26) and low ∂^{13}C values (–25.6 minimum value) typically contained low amounts of radionuclides. Pollen analyses are still underway, but have not as yet identified unequivocally sediments of Eurasian versus North American origin. Pollen is relatively uncommon in these samples, and when it occurs, is predominantly grass. Larch pollen, which is consistent with Eurasian forests, where the tree is more common than in North America, has been identified, but not in sufficient numbers to verify a Eurasian origin for specific samples. All of the sea-ice-entrained sediments have high proportions of silt and clay (83–99%), but there is no relationship (r^2=0.001) between fines content and radiocesium activities. When the silt and clay fractions are separated, radiocesium content significantly increased (on a dry-weight basis) in the separated clay in 5 of the 13 samples. Results of x-ray diffraction suggest that illite content may be related to radiocesium activities, but the correlation is not robust. To summarize, the samples with higher than expected radionuclide activity do not bear other sedimentary characteristics that would pinpoint their origin from documented, localized areas of relatively high radiocesium activity, such as the Yenesei River delta. Nevertheless, the available clay mineralogy data do not explain the higher activities observed in some of the samples. Additional studies, particularly of the mechanisms of radionuclide incorporation into sea-ice-entrained sediments, seem warranted.

For further information about this work, see:

Cooper, L.W., I.L. Larsen, T.M. Beasley, S.S. Dolvin, J.M. Grebmeier, J.M. Kelley, M. Scott, and A. Pyrtle-Johnson. 1998. The distribution of radiocesium and plutonium in sea ice-entrained Arctic sediments in relation to potential sources and sinks. *Journal of Environmental Radioactivity* 39 (3): 279–303.

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Anthropogenic Radioactivity in the Vicinity of the Bilibino Nuclear Power Station, Chukotka, Russia

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In past work near the Bilibino Nuclear Power Station in the Russian Far East, relatively high levels of anthropogenic radioactivity have been reported on vegetation, and in small mammals in the vicinity of the power station. During vegetation, soil, and water sampling conducted in 1995, we were unable to confirm that the power station is a significant source of anthropogenic radioactivity to the surrounding region. A localized area of radionuclide contamination was observed for at least 400 m downstream of an effluent discharge point into a small stream, underlain by permafrost, which drains the area surrounding the power plant. It appears likely that the localized contamination observed is the result of poor drainage and the lack of adequate mixing of the discharge, rather than radionuclide discharges that are significantly higher than those considered permissible under international standards. Trace-to-modest levels of radionuclides such as ^{54}Mn and ^{60}Co that are associated with nuclear energy generation were also detected on upland vegetation up to 4 km from the power station, indicating that airborne releases from the power plant are also a contributing factor to the overall radionuclide burden. Nevertheless ^{137}Cs inventories in soil suggest that weapons testing fallout is still the predominant anthropogenic radionuclide source for this region and that the Bilibino Power Station currently has no more than a very localized influence on the surrounding area.

For further information about this work, see:

Cooper, L.W., I.L. Larsen, G.L. Franklin, G.F. Houser, L.G. Emelyanova, and L.N. Neretin. 1996. Anthropogenic radioactivity in the vicinity of the Bilibino nuclear power station, Chukotka, Russia. *Polar Geography* 20: 3–19.

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POSTER PRESENTATIONS

Nutrient, Salinity, and Stable Oxygen Isotope Composition of Bering and Chukchi Sea Waters in Relation to the Arctic Ocean Nutrient Maximum

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Seawater nutrient, salinity, and oxygen-18 data collected from 1990–1993 in the Bering and Chukchi seas were used to identify potential sources of nutrients and water masses that result in formation of the Arctic Ocean upper halocline and its associated nutrient maximum. Water matching the $\partial^{18}O$ values of the Arctic Ocean upper halocline and containing sufficient, or a nearly sufficient, nutrient and salinity concentration was collected in the summer in portions of the Bering Sea, particularly the Gulf of Anadyr. Nutrient concentrations declined in this north-flowing water before it reached Bering Strait, as a consequence of biological utilization, and dilution with nutrient-poor freshwater. Therefore, there is no continuous path in summer of nutrient-bearing water with high enough concentrations of silica, nitrate, and phosphate to explain the formation of the Arctic Ocean nutrient maximum during summer from this source. Nevertheless, the $\partial^{18}O$ value of Arctic Ocean upper halocline water and the apparent $\partial^{18}O$ value of its freshwater end-member component is nearly identical with the $\partial^{18}O$ values of Anadyr water and its freshwater end-member component. This finding suggests that the Arctic Ocean upper halocline and nutrient maximum is formed from relatively unmodified Anadyr water flowing across the Bering and Chukchi Sea shelves over winter. During winter, low biological activity would prevent depletion of nutrients, potentially providing a Bering Sea source for similar, high-nutrient concentrations at the 100 m isobath of the Arctic Ocean.

For further information about this work, see:

Cooper, L.W., T.E. Whitledge, J.M. Grebmeier, and T. Weingartner. 1997. The nutrient, salinity, and stable oxygen-isotope composition of Bering and Chukchi sea waters in and near the Bering Strait. *Journal of Geophysical Research* 102 (C6): 12,563–12,573.

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Non-Redfield Carbon and Nitrogen Cycling in an Arctic Shelf System

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Molar concentrations and ratios of carbon and nitrogen associated with dissolved and particulate pools in the euphotic zone off the northeast coast of Greenland are assessed with respect to Redfield stoichiometry (C/N= 6.6). Inventories and rates include dissolved inorganic carbon and nitrogen, dissolved and particulate organic carbon and nitrogen, primary production and nitrogen uptake, zooplankton elemental composition, metabolism, and egestion. Only the C/N ratios for dissolved inorganic carbon to nitrate consumption and copepod respiration to excretion were not significantly different from Redfield stoichiometry; all other C/N ratios exceeded Redfield proportions. Elevated C/N ratios (8.9) of particulate organic matter appeared to be a response to nutrient and perhaps light limitation, particularly in large cells. Phytoplankton uptake ratios were similar to ratios of particulate organic matter only when urea was considered in addition to nitrate and ammonium. The dominant zooplankton, *calanoid copepods*, had elevated C/N body ratios (9.6) due to lipid storage. *Copepods* consumed on average 45% of the primary production, but provided <10% of the ammonium uptake by phytoplankton. Mass-balance calculations indicate that female *copepods* recycled ingested carbon in about equal proportions to biomass, fecal pellets, and dissolved organic carbon, while ingested nitrogen predominantly was excreted as dissolved organic nitrogen. Thus, *copepods* formed carbon-rich particulate matter, but resupplied dissolved pools at relatively low C/N ratios. The C/N ratio (17) of the dissolved organic pool significantly departed from Redfield stoichiometry, suggesting that dissolved organic carbon accumulated in the surface layer during summer, in part, resulting from relatively low bacterial abundance and metabolic rates. New production (35 mmol C m-2 day-1), estimated from the median integrated rate of nitrate uptake and the C/N ratio of particulate matter, was the same as the median thorium-234 particulate carbon export (Cochran *et al.*, 1995) and both estimates were 25% higher than new production estimated from the Redfield ratio.

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History of Holocene and Late Pleistocene Ice-Rafting Events

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The AOS '94 joint U.S. and Canadian Trans-Arctic Expedition collected valuable sediment box cores that record order-of-magnitude higher rates of sedimentation in the central Arctic Ocean than piston-core deposition rates averaged over the Brunhes interval (last 780 ka). Carbon 14 dating of the planktonic foraminifera provide detailed chronostratigraphy for the Holocene and some parts of the Late Pleistocene. Average Holocene deposition rates are 1–2 cm/ka. All sand-size, ice-rafted detritus (IRD) decreases from the last deglaciation event to the interglacial conditions of the Holocene, but the >0.25 mm IRD nearly disappears in the Holocene. Because sea-ice rafting transports mostly fine sand and smaller, the fluctuations of the >63 micron (fine sand) in all Holocene box cores reflect sea-ice rafting. All box cores from the central Arctic Ocean and most cores from the Chukchi Cap region show a 40–60% increase in fine sand IRD during the last 2–3 ka. This increase must indicate that the area of summer open water has increased on the marginal seas. This allows more wave activity which facilitates sea-ice entrainment in the fall. The sources of IRD in the central Arctic Ocean were determined by a fingerprinting technique using the chemical composition of detrital Fe-oxide grains. These grains were traced to source grain compositions from shelf areas using discriminant function analysis and probabilities of source identification of greater than 0.95. Intervals such as the Holocene are dominated by shelf sources while earlier IRD events (glacial IRD) come from shelf and inland sources. In both glacial and sea-ice rafting events, sources change rapidly. Where age constraints are good, IRD events from a single source area can be traced across the Arctic Ocean.

For further information about this work, see:

Bischof, J., D.L. Clark, and J.S. Vincent. 1996. Origin of ice-rafted debris—Pleistocene paleoceanography in the western Arctic Ocean. *Paleoceanography* 11 (6): 743–756.

Darby, D.A., J.F. Bischof, and G.A. Jones. 1997. Radiocarbon chronology of depositional regimes in the western Arctic Ocean. *Deep-Sea Research II* 44 (8): 1745–1757.

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Pollen Records on Baffin Island Indicate Response to Climate Change Starting about A.D. 1890

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Pollen records from two varved lakes on southern Baffin Island, Ogac Lake, and Winton Bay Lake, indicate that pollen parameters of the past 100 years are markedly different than those of the preceding 1,000 years. This trend is indicated in both local and exotic pollen types and revealed by multivariate clustering analysis (CONISS). The two sites are located hundreds of kilometers apart and the local climates are distinctly different with Ogac Lake bordering the relatively sheltered Frobisher Bay and Winton Bay Lake proximal to Davis Strait. A third varved site, Upper Soper Lake, near Lake Harbor on the southern boundary of Baffin Island, is under investigation. We interpret these results as evidence that the low arctic vegetation on Baffin Island shows a response to post-Little Ice Age warming. The unique signature of the pollen record for the past 100 years within this millennia suggests that, regardless of the cause, arctic vegetation is undergoing significant changes this century.

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Holocene Vegetation History of a Peat Deposit from the Meade River Sand Bluffs in Northern Alaska

Wendy R. Eisner[1] (University of Alaska Anchorage) and Kim M. Peterson[2]

The first detailed analysis of a peat deposit from the Meade River bluffs near Atqasak, on the Gubik Sands of the Alaskan Arctic Coastal Plain demonstrates chronological control is obtainable from these sediments, and microfossil assemblages reflect both climatic change and local vegetation succession over a 10,000-year period. Changes in peat accumulation reflect not only climatic change, but are also influenced by geomorphic processes of river meandering, wind erosion, and sand deposition.

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How Large are the Regional Differences in Surface Heat and Moisture Fluxes in Alaskan Arctic Tundra?

Werner Eugster[1] (University of California Berkeley), F.S. Chapin, III,[2] G.L. Gamarra,[3] and J.P. McFadden[4]

To assess the regional variation in surface heat and moisture fluxes on the North Slope of Alaska, we used a new experimental approach to flux measurements—portable, mobile eddy covariance instrument towers. The question is: how many landscape or vegetation types have to be distinguished in the arctic tundra, to be able to represent this environment adequately in mesoscale, meteorological-, or global-scale climate models (MM4; GCM)? We present first results from the field season 1995.

For further information about this work, see:

Eugster, W., J.P. McFadden, and F.S. Chapin. 1997. A comparative approach to regional variation in surface fluxes using mobile eddy correlation towers. *Boundary-Layer Meteorology* 85 (2): 293–307.

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Climate and Lake-Level Change in Interior Alaska

Bruce Finney[1] (University of Alaska Fairbanks), Mary Edwards,[2] and Valerie Barber[3]

Better estimates of past effective moisture and hydrologic conditions are needed for verification of GCMs and regional climate models. Little paleohydrology has been attempted in the Arctic and subarctic, yet over late-Quaternary time scales it is probable that precipitation, effective moisture, and hydrologic regimes varied dramatically, affecting vegetation composition and ecosystem processes. Interior Alaska currently has a semi-arid climate, and lake levels, especially those in closed basins, should be sensitive to changes in effective moisture. The region was unglaciated in Quaternary time and lakes potentially contain long paleoenvironmental records. We are studying past lake-level changes at four lakes (Birch, Dune, Jan, Sands of Time) in interior Alaska. Paleo-lake levels have been determined from transects of lake-sediment cores (combined with seismic profiling at Birch). All lake basins record low water levels prior to 12,000 ^{14}C year BP. Subsequently there was rapid filling, which coincides with a rapid, widespread vegetational shift from herb to shrub tundra, and which is likely related to a major change in hemispheric circulation. A minor low stand is recorded in the early Holocene, which coincides with the interval of strongest summer heating simulated by GCMs. Modern water balance models for Birch and Jan are based on meteorologic and hydrologic data. Sensitivity tests were run corresponding to the lake-level reconstructions for 6,000 and 12,000 ^{14}C year BP. Equilibrium solutions for precipitation were determined for a set of evaporation (lake) and evapotranspiration (catchment) values. At 12,000 year BP levels of both lakes (Birch -11 m and Jan -9 m) are consistent with precipitation 25–60% of present. At 6,000 year BP the levels (Birch -0 m, Jan -6 m) are consistent with precipitation of 80–90% of present. The results show that even though the lakes have different basin characteristics, a constant solution can be obtained for each time slice.

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A Protocol for Gathering Local Knowledge about Caribou

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Much discussion has taken place on the need for incorporating local knowledge into arctic biological research. The initiative for this incorporation has come because of the way that science has been used for making management decisions on resources that arctic residents use. How to include such information in research, however, has remained an open question. Several recent findings in caribou research suggest that abiotic factors have an influence on important caribou population parameters. These factors are often episodic and not easily captured in data samples. As people on the land, caribou hunters are constant observers of the environment. A way in which to gain more data on episodic events affecting caribou is to seek these hunters' observations. If significant, such information could become essential for the basic science of caribou. Reported here are:

1. a discussion of the mathematical theory behind incorporating qualitative data in quantitative models,
2. a preliminary methodology and protocol for gathering local information, and
3. a description of the results obtained in a pretest of that protocol.

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Simulating and Detecting Deep Water Formation in the Greenland Sea and Coastal Arctic—The Arctic Connection with the Global Oceans

Roland W. Garwood, Jr.[1] (Naval Postgraduate School) and Lin Jiang[2]

We summarize model results and observational evidence of open-sea and coastal deep convection. Large-eddy simulation of small-scale nonhydrostatic convective plumes compares favorably with deep convection observations. The theory and LES model results provide a plausible mechanism for super-penetrative convection in which near-surface water convects to the deeper ocean with minimal mixing with the intermediate water masses, consistent with observations. We show results of a new model parameterization for subgrid deep convection to be included in oceanic general circulation and climate models. Coastal and cross-shelf plume convection is also simulated, showing the three-dimensional character of topographically influenced bottom plumes. These model results may explain satellite observations of what appear to be the surface manifestation of bottom water plumes exiting Denmark Strait. This intriguing result suggests a new way of monitoring the connection between the Arctic and the global oceans by remote sensing.

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GISP2—An Ice Core Time Machine

GISP2 PIs[1] (University of New Hampshire)

On July 1, 1993, scientists and drillers of the Greenland Ice Sheet Project Two (GISP2) reported from Greenland via satellite that the final section of the world's deepest ice core had just been retrieved after five consecutive, several-month-long field seasons of effort by scientists and drillers from 20 U.S. research institutions. The ice core, 13 cm in diameter and 3053.44 meters in length, provides the longest, most detailed, most extensively and broadly analyzed continuous record of climate from the northern hemisphere ever retrieved. Results from this record have already provided dramatic insights into climate and climate change. Interpretation of results over the next few years promises to revolutionize our understanding of climate, and of humanity's role in climate change. The Greenland ice sheet contains a unique history of climate for the northern hemisphere. Chemicals, gases, dust, and other atmospheric constituents are trapped in the snow that falls over the Greenland ice sheet. By drilling an ice core from the ice sheet and analyzing the recovered ice, researchers obtain a direct record of past climate. Unlike deep-sea sediments, the record is continuous—each year's snowfall is represented in the core. And unlike tree rings, the ice-core record will extend beyond the last few thousand years and through the previous glacial cycle. Even more importantly, this ice-core record provides a measure of both environmental and climate change and the causes of such change.

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Hydrographic and Benthic Data from the East Siberian and Chukchi Seas

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Seventy-one stations were occupied 17 August–5 September 1995 for a hydrographic and sediment survey from the mouth of the Kolyma River in the East Siberian Sea to Bering Strait in the Chukchi Sea. The goal of this joint U.S.-Russian oceanographic cruise was to study oceanic processes and assess contaminant levels within the Siberian Coastal Current that flows eastward towards the Alaska mainland as well as in offshore waters in both seas. Physical oceanographic measurements indicated two separate water types occupied each sea, with freshwater from the Kolyma River limited to the East Siberian Sea during this period. Both surface and bottom water temperatures were lowest in the East Siberian Sea where the ice concentrations were greatest. Surprisingly, the highest water column chlorophyll a concentrations occurred in the East Siberian Sea, with values ranging from 3–182 mg/l, compared to 1–20 mg/l in the Chukchi Sea. Chlorophyll content of surface sediments ranged from 1 mg/g nearshore to 10 mg/g offshore, with values reaching up to 26 mg/g in the East Siberian Sea. Sediment oxygen uptake rates, an indicator of carbon flux to the benthos, were highest in the eastern Chukchi Sea (20–26 mmol O_2/m/d), generally declining towards the western side of the East Siberian Sea (1 mmol O_2/m/d), except off the mouth of the Kolyma River. Surface-sediment total organic carbon content ranged from <1.0 to 1.5% in both seas, with the highest values (up to 2.2%) occurring in the central Chukchi Sea. C/N values ranged from 5–8, with the highest ratios near the mouth of the Kolyma River. Surface water dissolved ^{137}Cs (an anthropogenic radioisotope) activities were lowest in the East Siberian Sea compared to the Chukchi or Bering seas. Surface sediment ^{137}Cs activities were lowest nearshore (1 Bq/kg), rising to 6 Bq/kg offshore in both seas. Preliminary data indicate that organic carbon produced in the water column is not being incorporated into the surface sediments or benthic fauna in the East Siberian Sea, unlike the Pacific-influenced eastern Chukchi Sea, but is likely being advected offshore across the wide continental shelf towards the arctic basin.

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Environmental Change in Iceland Last >10,000 Years—Results from Lake Sediments

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POSTER PRESENTATIONS

The joint Icelandic/USA PALE initiative is the first effort to systematically establish the Late-glacial and Holocene climatic history of Iceland with good spatial and temporal resolution. Preliminary results from sedimentological, rock magnetic, diatom, and pollen studies on lake sediments retrieved from five lakes in southern and western Iceland show very interesting results:

1) a threefold division of environmental parameters during the last 6,000 years and
2) revolution of the existing ideas about Younger Dryas ice and sea-level extent in southern Iceland if preliminary dating of the oldest sediment prove right.

Future studies aim to study possible transgressive climate changes through continuing lake studies from other parts of Iceland, and to investigate the climatic variability between the lacustrine and marine environments.

For further information about this work, see:

Geirsdottir, A., F. Hardardottir, and J. Eiriksson. 1997. The depositional history of the Younger Dryas—preboreal Budi moraines in south-central Iceland. *Arctic and Alpine Research* 29 (1): 13–23.

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The Paleoclimate Signal from Arctic Lake Sediments

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Raymond S. Bradley,[3] and Michael Retelle[4]

Laminated lacustrine and marine sediments offer the potential of providing a pan-arctic network of annual-resolution paleoclimate proxy records. We are investigating the processes by which climate influences the delivery of sediments to lakes in the Canadian High Arctic. Within this large region, there are numerous lakes containing annually laminated sediment archives, yet only a few long-term instrumental climate records and no permanent stream-gauging sites. This lack of climatic and hydrologic data creates uncertainty about the spatial variability of the physical processes influencing streamflow and sediment transfer, making the calibration of sediment proxy records with respect to climatic variability problematic. The three study sites at which we have undertaken comprehensive field investigations illustrate the variability of summer climate and sediment delivery systems in the Canadian High Arctic. Among the three sites Lake C2, on the north coast of Ellesmere Island (82°50' N; 78°00' W), receives the most winter precipitation and experiences the coldest summers (and, hence, least rainfall). Consequently, sediment transfer each summer is primarily a response to the energy available for snowmelt. The most southern site, at Sophia Lake (75°06' N; 93°31' W), is a relatively low-relief basin of carbonate lithology, resulting in exceptionally low suspended sediment concentrations. Nonetheless, following a brief period of snowmelt runoff, summer rainfall events in 1994 produced streamflow responses which may also be recorded in the sediment record. The third study site is adjacent to the Agassiz Ice Cap, at Lake Tuborg on Ellesmere Island (80°58' N; 75°23' W). Runoff of melting winter snow from the surface of the glacier dominated streamflow in 1995. The relatively low slope of the snow-covered, ice-cap margin impeded meltwater runoff during a period of rapid snowmelt, inducing a slushflow during which suspended sediment concentration reached over 3,000 mg/L. The recurrence interval for an event of this magnitude is unknown, but such events de-couple the linkage between climate and sediment transfer. Lake C2 has provided a 200-year proxy record of summer temperature, and efforts to extend this record back several thousand years are in progress. On-site monitoring provided an understanding of contemporary sediment delivery and allowed calibration of the laminated sediments. However, preliminary analysis of field measurements and sediment cores from these other two sites suggests that calibrating sediment thickness to a single climate variable may not be accurate and reliable at all sites.

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Integrated Investigations of the Active Layer at Barrow: Monitoring Program, Analysis, and Results

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During 1995, several separate but related studies were conducted in and near the ARCSS/LAII 1 km site at Barrow. The purpose was to assess temporal and spatial effects of physical processes on the characteristics of the active layer and upper permafrost. One component entailed monitoring and modeling heat and moisture transfer in the near-surface region throughout the year. A second involved a concerted effort to quantify long-term changes in the physical and chemical properties of the upper soil profiles. Barrow is unique on the North Slope because soils have been studied here for several decades. By resampling at previous core extraction sites, long-term changes in ice content and soil-carbon content can be determined. Finally, an effort was made to quantify the degree of variability in the thickness of the active layer at differing spatial scales by intensive sampling on progressively smaller plots. These interrelated studies will allow us to identify the major factors that control active-layer thaw, and to determine how these factors influence local heat- and mass-transfer processes in the near-surface region, ice enrichment in the upper permafrost, and soil-carbon sequestering in the soil column. Preliminary analysis of this information yields the following general conclusions:

1. The physical processes that determine active-layer thaw depths are very localized, yielding highly variable thaw depths at the landscape and sub-landscape scale.
2. It is possible that the variability of active-layer thickness does not scale consistently between sites characterized by different vegetation units, soils, and topography. Measures of central tendency (mean, mode) are more robust throughout a hierarchy of scales.
3. The ice content of the upper permafrost appears temporally nonstationary at the annual and decadal scale, but this may be an artifact of lateral heterogeneity.

For further information about this work, see:

Hinkel, K.M., F.E. Nelson, Y. Shur, J. Brown, and K.R. Everett. 1996. Temporal changes in moisture-content of the active layer and near-surface permafrost at Barrow, Alaska, USA—1962–1994. *Arctic and Alpine Research* 28 (3): 300–310.

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Local Controls on Active Layer Thaw: Results from the ARCSS/LAII 1 km Grids

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Although active-layer thaw depth is largely controlled by surface temperature and thus has a regional pattern, it can vary significantly over short distances. This component of the project is designed to assess the magnitude and significance of this spatial variability, to monitor the spatial and temporal patterns of thaw over single and multiple seasons, and to identify and model the influence of local factors on thaw depths and patterns. The active layer is of interest to the flux study for several reasons:

1. a systematic thickening could increase the net annual efflux of radiatively active greenhouse gases;
2. it is important to determine the degree to which localized studies represent larger regions, so that results can be extrapolated spatially to larger scales; and
3. any effort to model active-layer processes requires knowledge of the dominant factors affecting thaw and freezeback.

The methodology entails physical probing with a rigid metal rod on the 1 km ARCSS grids at Barrow, Atqasuk, West Dock, Betty Pingo, Happy Valley, Imnavait Creek, and Toolik Lake. At each site, the 121 grid nodes were probed 3–4 times during the summer of 1995. Analysis of the mapped patterns yield several conclusions:

1. Active-layer thaw is enhanced in moist regions, especially near lake margins, thaw lake basins, wet lines, and stream valleys. Thaw depths at these sites are often greater by a factor of two and can show a very high degree of spatial variability, necessitating high-density sampling.
2. Local topography has a measurable impact on thaw depth by affecting patterns of snow drifting and incident radiation loading.
3. Concurrent sampling of soil conditions (texture and moisture), vegetation units, and soil temperature will aid in isolating and modeling those factors which, at the landscape scale, influence active-layer thaw.

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Plant/Soil Modeling in Kuparuk Basin

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Bonnie L. Kwiatkowski[3]

We use the Marine Biological Laboratory's General Ecosystem Model (MBL-GEM, Rastetter *et al.*, 1991) to investigate the responses of arctic tundra to changing climate conditions. MBL-GEM simulates ecosystem response to changes in the climate drivers: carbon dioxide concentration, temperature, soil moisture, light intensity, and nutrient inputs. Model outputs include net primary production (NPP), soil respiration, net ecosystem production (NEP), and plant and soil stocks. In tussock tundra, the nutrient modeled is nitrogen which has been shown experimentally to be the limiting nutrient. In wet-sedge tundra, phosphorus is often limiting and hence is modeled as the limiting nutrient. Using MBL-GEM, calibrated with data from experiments at Toolik Lake for tussock tundra (McKane *et al.*, 1997a and 1997b) and wet-sedge tundra, we simulate the response of tussock and wet-sedge tundra to a doubling of carbon dioxide concentration and the simultaneous changes in temperature, soil moisture, and light. The results show an increase in ecosystem NPP due to the increase in CO_2. This increase in NPP is enhanced by the effects of temperature and decreased by the effects of soil moisture and light.

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McKane, R., E. Rastetter, G. Shaver, K. Nadelhoffer, A. Giblin, J. Laundre, and F. Chapin. 1997(b). Reconstruction and analysis of historical changes in carbon storage in arctic tundra. *Ecology* 78: 1188–1198.

Rastetter, E.B., M.G. Ryan, G.R. Shaver, J.M. Melillo, K.J. Nadelhoffer, J.E. Hobbie, and J.D. Aber. 1991. A general biogeochemical model describing the responses of the C and N cycles in terrestrial ecosystems to changes in CO_2, climate, and N deposition. *Tree Physiology* 9: 101–126.

Arctic Sea-Ice Circulation Using a Coupled Sea-Ice, Ocean, Land, and Atmosphere Model

David M. Holland[1] (Columbia University)

The arctic sea-ice thickness, concentration, and velocity is predicted using a thermodynamic-dynamic, sea-ice model coupled to a planetary boundary layer atmosphere model, a slab ocean, and a land model. The key point made is that the prognostic sea-ice simulation is being made alongside with prognostic air temperatures. The more traditional approach is to specify apriori the air temperatures and then to compute the sea-ice characteristics. That approach, however, can not lead to an understanding of the coupling and/or feedbacks between the sea ice and the lower atmosphere. The approach taken in this study is a step towards a better understanding of the coupling between the sea ice and lower atmosphere.

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Reconstructed Paleoclimate Records from Varved Arctic Lake Sediments, Baffin Island, Canada

Konrad Hughen[1] (Harvard University), Jonathon Overpeck,[2] John Moore,[3] and Lisa Doner[4]

Reconstructing spatial patterns of climatic change in the Arctic is important to understanding forcing mechanisms within the region and possible linkages to other climate systems. Annual paleoclimate records from varved lake sediments are ideal for spatial reconstructions because they provide precise and accurate dating control and are relatively common in arctic regions. Laminated sediments from Upper Soper Lake, Ogac Lake, and Winton Bay Lake on southern Baffin Island, are known to be annual varves on the basis of ^{210}Pb and Pu analyses. Light and dark laminae thickness from Upper Soper Lake, near the settlement of Lake Harbour, were measured independently on three cores, averaged, and then compared to Lake Harbour meteorological records for calibration. Meteorological data were recorded at Lake Harbour from 1923 to 1945. Dark laminae thickness showed the best fit compared to average June temperature. The varve chronology was "adjusted" by the addition of a single varve not measured in the original count but visible in sediment thin sections. A scatter plot of dark laminae thickness versus June temperature shows a strong linear correlation (r=.87), indicating 77% of the dark laminae thickness variability can be explained by Lake Harbour June temperature. This agrees with theory in that the thickness of dark laminae, consisting of clastic grains washed into the lake, should be influenced by the intensity of snowmelt runoff in the spring. June is the first month in the region with above-zero average temperatures, and terrestrial grains are first available to be mobilized, depending on the strength of runoff. Donard Lake, near Cape Dyer on eastern Cumberland Peninsula, is a glacial-fed lake with clastic laminated sediments. Laminae counts agree with a calibrated radiocarbon date of 950 year BP, indicating that the laminae are annual varves. Varve thicknesses measured in a single core for the period 1959–1990 were compared to average summer (JJA) temperatures from the DEW site at Cape Dyer, showing a good correlation (r=.68). Increased summer temperatures result in greater glacier melting and increased sediment input to the lake basin (thicker varve). Varve and laminae thickness records from Ogac and Winton Bay lakes have not yet been quantitatively calibrated with meteorological data, but nonetheless provide precise dating control for other paleoclimate proxies, particularly pollen. Pollen records from these lakes agree in general with reconstructed climate from Upper Soper and Donard lakes. These existing sediment records from Baffin Island lakes, in addition to varve records from other High Arctic lakes, will be used to extend spatial comparisons further back in time. A network of high-resolution paleoclimate records is integral to understanding the spatial patterns of regional climatic change and the mechanisms influencing those patterns.

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High-Resolution Changes of Paleoceanography on the Western Iceland Shelf

Anne E. Jennings[1] (University of Colorado-Boulder), John T. Andrews,[2] and James Syvitski[3]

In 1993 the CSS Hudson undertook a cruise from Iceland to East Greenland as part of the Canadian contribution to PALE. During the cruise, high-resolution seismic data were collected (airgun and Huntec) on the west Iceland shelf as well as on the margin of east Greenland. The Long-Coring Facility (LCF) giant piston corer was employed, as were gravity cores, trigger cores, and 0.5 x 0.5 m box cores. In Flaxafloi in ca. 250 m water depth we obtained a 16 m LCF core. We have obtained a suite of AMS ^{14}C dates on the core and shown that the cores extend from the Allerod to the present. A feature of the core is a sandy layer which is younger than 11.1 ka (uncalibrated). Inspection of this zone, and geochemical analysis indicates that the sand is made up of volcanic ash which is geochemically identical to the Vedda ash, dated on land in Norway ca. 10.3 ka. Inspection of the seismic records indicates that the Vedda ash is visible on the seismic records as a major reflector which can be traced across the west Iceland shelf for 10s of kilometers. The poster will illustrate the faunal changes between ca. 10 and 12 ka, and the seismic stratigraphy of the region. This poster is a contribution to the USA/Iceland PALE project involving both Icelandic and U.S. researchers.

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Winter Intensification and Water Mass Evolution in the NEW Polynya

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In the summer of 1992, four current meter moorings were deployed in, and later retrieved from the East Greenland Shelf by the USCGC Polar Sea. The moorings provided hourly temperature, salinity, and current data for approximately one year. The data characterize the NEW region in four ways. First, the circulation intensifies during winter while the steadiness of the current increases as well. Intensification is most readily observed at 150 m on the southern side of the northern trough system. Second, the surface layer freshens from summer through December due to freshwater runoff. From December through early spring, salinity increases due to brine rejected during ice formation. A water mass termed Northeast Water Polynya Intermediate Water is found at 75 m. Wintertime events show water at the freezing point at this depth. Knee Water (Bourke *et al.*, 1987) has not been observed in the current meter data, nor observed to enter the NEW. Third, short-lived events of three-to-seven days duration perturb the T-S character at each of the current meter depths providing evidence for local water mass formation and advection through the NEWP region by eddies. These events perturb the T-S characteristics at each depth so that T-S values found generally at 75 m are observed at 150 m, and T-S values found generally at 150 m are observed at 250 m. Lastly, on the northern side of the polynya's northern trough, the current meter data provide direct evidence for westward flow into the polynya region at a depth of 250 m. This southwesterly current along the northwest slope of the trough at 250 m is in agreement with the summertime ADCP measurements from NEWP92.

For further information about this work, see:

Topp, R., and M. Johnson. 1997. Winter intensification and water mass evolution from yearlong current meters in the Northeast Water Polynya. *Journal of Marine Systems* 10 (1–4): 157–173.

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Arctic Tundra CO_2 Flux in Winter and Summer: Effects of Snow Cover and Temperature on the Annual CO_2 Balance

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Arctic climate models in general agree that weather conditions in winter and in summer are likely to be different in the future as compared to those at present. These changes may include increases in snowfall along with warmer summer temperatures. The ecological consequences of both winter and summer climate changes are, however, unclear, especially with regard to changes in rates of winter heterotrophic respiration and the balance between summer photosynthesis and summer respiration. As part of our International Tundra Experiment (ITEX) field manipulations, we have been examining the interactive effects of altered snow cover and warmer summer temperatures on organismic and ecosystem-level processes at Toolik Lake, AK. Snow fences (60 m x 3 m) were built in moist and dry tundra to alter snow depth in winter. Summer temperatures are elevated using open-top chambers in four snow depth zones ranging from very deep snow cover to ambient snow cover depth in winter. We have measured CO_2 flux under snowpack in deep and ambient snow cover over the past two winters (1994–1995 and 1995–1996) and we have measured summer net CO_2 flux between June and August in 1995 only. We have found significant CO_2 flux through snow to the atmosphere from both moist and dry tundra in both winters. CO_2 flux in winter through snowpack is generally greater from moist, as opposed to dry, tundra and some interannual variability exists due in part to conditions in fall and in early winter as the snowpack was developing. In the winter 1994–1995, increasing snowpack on moist tundra had almost no effect on winter CO_2 flux, while dry tundra under deep snow had 2 x the CO_2 flux rates as adjacent areas under ambient snow cover. Similar findings were observed again in the winter of 1995–1996. Thus, while the CO_2 flux rates are low in winter, arctic tundra during the winter is, in general, a CO_2 source for atmospheric carbon dioxide. Net CO_2 flux from tundra to the atmosphere in summer was greater in moist, as opposed to dry, tundra. Over the summer both sites appear to be net sources of CO_2 as opposed to sinks, though our measurements did not begin until late June. Warmer temperatures in dry tundra resulted in increases in CO_2 loss but temperature had no effect on the net flux of CO_2 from moist tundra, nor did the depth of snow cover in the previous winter. Snow cover in the previous winter did, however, influence CO_2 flux in dry tundra during the summer. Our findings suggest that the annual

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CO_2 balance of both moist and dry tundra may have been negative in recent years, where both tundra types have acted as CO_2 sources. We postulate that the annual cycle of net carbon exchange between tundra and the atmosphere may be predicated on annual weather conditions in the fall and early winter as well as in spring. The fall transition period sets the over-winter soil and snow-cover conditions which in turn regulates winter CO_2 efflux. Spring and early summer conditions set the stage for the growing season balance between photosynthesis and respiration, and the summation of winter and summer CO_2 flux represents the net carbon dioxide exchange between tundra ecosystems and the atmosphere.

Integration of Snow Process Studies and Hydrologic Analyses

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The arctic tundra is covered with snow for eight to nine months each year. This persistent snow cover directly or indirectly impacts most physical and biological processes. Even analyses of summertime hydrologic and thermal processes must rely upon a firm understanding of the precursor winter conditions. Snow distribution is one of the dominant controls of the winter heat flux from the surface. This winter heat loss is one of the controlling factors on the depth of the active layer in the following summer and can directly impact vegetation survival, soil moisture levels, and erosion of soil. The amount and distribution of snow also controls the timing of spring snowmelt on many scales and the volume and intensity of snowmelt runoff. To understand the spatial dynamics of ecosystem response to climatic change, the snowpack distribution must be determined at several spatial scales. With great effort, in both field measurements and laboratory analyses, it is possible to develop excellent maps of snowpack distribution over small areas. These high-resolution maps provide the mechanism to understand interactions among snow, vegetation, thaw depth, soil moisture, nutrient dynamics, and other important topics. However, the labor intensive method of developing these snow distribution maps cannot realistically be applied to large areas such as the entire Kuparuk River watershed. To accomplish this goal, we must consider a more process-based approach. We must utilize the knowledge that we gained in the Imnavait Creek watershed and elsewhere to develop extrapolation methods which will enable accurate snow distribution maps of greater and greater areas. Two methods of mapping snow distribution have been used at Imnavait Creek: an "expert" method, and a grid sampling method. The expert method produces maps with high veracity and potentially unlimited detail. The "experts" who do the mapping also develop a qualitative sense of how the snow is distributed on the landscape that is potentially useful in extrapolating to new areas of similar landscape type. However, it takes an enormous amount of time and effort to develop the expertise that goes into the map. For large areas, developing such local expertise is impossible. Sampling on a grid is simpler than the expert system, though even with a high point density, only major trends can be captured. It also requires judgment in choosing the grid spacing. As we have shown, snow depth on the tundra is affected by two scales of variance: large-scale topographic features and smaller microtopographic and vegetation features. In addition, a grid must be established on which the

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sampling is to be done. Even once the grid is established, the sampling requires significant time. A typical snow survey for Imnavait (231 depths/km^2) requires many man-hours and installation of the grid took hundreds of hours more. Neither the expert nor the grid method are suitable for large-scale snow mapping in the Kuparuk Basin, the Arctic Coastal Plain, or the circumarctic. For example, the Kuparuk Basin is about 8000 km^2. To produce maps at the detail shown above using a grid sampling system like that at Imnavait Creek would require 2 man-years for sampling! If the data density were reduced by a factor of 10 (20 points per km^2) the work would still take months, and the resulting map would contain no trend information at the kilometer level. Our conclusion is that a combination of both methods is required. From the expert method, we derive the fundamental relationships between the snow and the landscape. These relationships can take two forms,

1. empirically based relationships between vegetation, topography, and snow cover, or
2. physically based relationships which allow a computational evolution of the snow cover throughout the winter, based on the interactions between the atmospheric forcing and the landscape.

We use a sampling method to calibrate and test these relationships. This combined approach is appropriate for the Kuparuk Basin, and if it proves successful there, for larger areas of the Arctic.

Passive Microwave Remote Sensing of Arctic Land Surface Conditions

Edward J. Kim[1] (University of Michigan) and Anthony W. England[2]

Land-surface processes and feedbacks have been identified as key uncertainties that affect predictions of climate change. These processes are complex and interrelated. For example, the surface albedo feedback due to snow had been viewed as a simple positive feedback (*i.e.*, warmer temperatures decrease snow cover, darkening the surface and resulting in increased absorption of solar radiation), but a recent study indicated this explanation to be overly simplistic—cloud interactions and longwave radiation may also influence the process. Similarly, warmer summers in the Arctic will stimulate plant growth which may have a positive feedback in addition to various ecological consequences. The 1992 Supplementary Report of the Intergovernmental Panel on Climate Change cited the lack of adequate observational data as a serious impediment to climate model improvement. This is particularly so in the Arctic, and satellite remote sensing may be the only practical means of observing climate-forcing variables at frequent intervals (perhaps daily or semi-diurnally) over large areas at useful resolutions. Microwave remote sensing offers advantages that are particularly well suited to the observation of high-latitude regions. Microwave sensors are far less susceptible to interference by clouds than are optical or infrared sensors, and they are not dependent upon solar illumination, permitting observations at night and throughout the polar winter. Microwave radiometry is particularly sensitive to temperature and moisture distributions in vegetation canopies and in the underlying soil. These quantities are, in fact, the gross physical parameters of greatest significance in land-atmosphere boundary processes. We are developing a land-surface-process/radiobrightness (LSP/R) model for arctic tundra that is linked to satellite observations. Such models provide land-atmosphere boundary conditions and feedback for atmospheric circulation models such as the arctic region climate system model (ARCSyM). The LSP/R model is a biophysical representation of the linkage between the observed emission and conditions deeper within the canopy and the soil. By using observations made over a period of time to constrain this model, subsurface temperature and moisture conditions may be determinable for simple vegetation such as tundra and grasslands. While the LSP/R model is too computationally intensive to be an operational LSP model for ARCSyM, it can be run retrospectively for selected regions to obtain much higher fidelity estimates of temperature and moisture profiles within tundra than would be available from an operational LSP model. Several modeling issues, including a scaling strategy, will be highlighted. By linking the LSP/R model to satellite observations, the performance of the model over a region such as the North Slope of Alaska can be monitored and estimates of surface temperature and depth and moisture content of the active layer with a spatial resolution of ~40 km—the average resolution of the Special Sensor Microwave/Imager (SSM/I) satellite instruments—should be possible. Data from our

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Radiobrightness Energy Balance Experiment 3 (REBEX-3) are supporting model development. The data were collected for one full annual freeze-thaw cycle at a wet acidic tundra site on the North Slope. Example data will be presented along with a snow-covered/snow-free frozen/thawed remote classification scheme for tussock tundra.

Carbon Dynamics in Prudhoe Bay Surface Waters

George Kling[1] (University of Michigan), Larry Hinzman,[2] Douglas Kane,[3] James McNamara,[4] and John Hobbie[5]

The objective of this study was to uncover mechanisms controlling the fluxes of carbon from surface waters in a tundra wetland complex near Prudhoe Bay. A hydrologic field-monitoring program and a comprehensive chemical sampling program were initiated to describe the water and chemical budgets of several ponds and lakes. In this poster we assume Na+ acts as a conservative tracer and compare its concentrations to the concentrations of various carbon speciations. Consequently, by evaluating the changing concentrations through the season in conjunction with water balances in the ponds and lakes we can infer the relationships between carbon flux and the hydrologic cycle. Water samples were collected weekly, filtered through GF/F filters, and preserved with acid. Na+ concentrations were determined direct current spectrophotometry (DCP), and DOC concentrations were determined by a high-temperature platinum-catalyzed combustion (Shimadzu TOC-5000). Partial pressures of CO_2 were determined directly; water samples were collected in syringes and a headspace equilibration with air was performed. The headspace gas was then analyzed by gas chromatography. Conclusions of this study are:

1. The water balance of these lakes during the summer is driven mainly by evaporation and by some inflow of rainwater.
2. Because there are no large stream inflows or outflows, the chemistry of the lakes is controlled mainly by evaporative concentration and by in situ biological processes.
3. CO_2 concentrations increase in the lakes over the summer, but at a lower rate than the increase of the conservative ion Na+. The loss of DOC relative to Na+ indicates consumption of DOC by bacterial uptake or by conversion to CO_2.
4. CO_2 pressures in the lakes are usually greater than the atmospheric pressure of CO_2, indicating a net flux of CO_2 from the lakes to the atmosphere.
5. CO_2 pressures in the lakes decrease in early summer due to the uptake of CO_2 by algae or aquatic macrophytes during photosynthesis.
6. CO_2 pressures in the lakes increase in late summer due to the respiration of organic matter. Note that the net increase in CO_2 is positive, indicating that the loss of CO_2 by evasion to the atmosphere is less than the gain of CO_2 from in-lake respiration.

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Distributed Modeling of Thermal Processes in the Kuparuk River Basin

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There is ample evidence which now indicates that the global climate is warming. To investigate the effects of climate change on the thermal processes in arctic tundra, a one-dimensional heat conduction model has been developed. The model was formulated using a finite element technique and includes the effects of phase change and variable properties. A surface energy balance model has been coupled with the heat conduction model to solve the one-dimensional heat transfer problem within the active layer and permafrost. Equations representing the interacting processes of the surface energy balance are solved simultaneously for the surface temperature which is then used to drive the subsurface heat conduction model. This model simulates the subsurface temperature and depth of thaw. A spatially distributed model was designed to calculate the surface and subsurface temperature and thaw depth on a grid encompassing the Kuparuk River Basin. The meteorological input data for the distributed model are collected at 7 met stations across the North Slope and distributed spatially using a kriging method. The finite element model coupled with the energy balance model calculates soil surface and subsurface temperature and thaw depth. These programs were written to operate on a UNIX-based workstation; however, the codes are being parallelized on the Cray T3D supercomputer. This model is based on the thermal energy balance method and considers slope, aspect, and surface conditions in addition to vegetation and soil moisture to calculate surface temperature. This thermal model when coupled to a hydrologic model can provide information valuable in the analysis of biological and physical processes, such as trace gas emissions and nutrient transport.

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Regional Modeling for Arctic Tundra Ecosystems: Performance of the Arctic Region Climate System Model (ARCSyM) and Data Assimilation Using MM5

Amanda H. Lynch[1] (University of Colorado-Boulder), Jeffrey S. Tilley,[2] William L. Chapman,[3] David A. Bailey,[4] and John E. Walsh[5]

The purpose of this project is to provide a linkage between the LAII Flux Study's field measurements and the broader issues of regional and global climate in the Arctic. The strong sensitivity of polar climate to the simulated surface fluxes of heat, moisture, and momentum and the small scale of many of the important processes undoubtedly play a role in the deficiencies in the simulations of the Arctic by global climate models. The approach we have taken to reach an understanding of the role of the Arctic in climate is a high-resolution limited area model system approach. This approach, while computationally expensive and difficult, is physically based and has yielded promising preliminary results, hence offering a wide range of applications. The goals of this work are:

- to assess the performance in the western Arctic of a selection of land-surface/vegetation parameterizations (BATS, LSM, and CLASS);
- to provide an optimized model to act as a basis upon which interpretation and regional integration of field observations can occur;
- to project climate and hydrological changes in the Arctic related to various climate change scenarios; and
- to produce regional estimates of CO_2 fluxes from tundra under current and postulated climatic regimes.

To this end, work is proceeding in three phases. First, the land surface/vegetation packages are being tested in a one-dimensional, "stand-alone" mode, forced by Flux Study field observations, to determine their behavior and response to changes independently of the climate system model. The second phase of the project consists of the implementation of the aforementioned land-surface/vegetation packages within ARCSyM, and an examination of the impact of these packages on coupled annual cycle climate system simulations. Finally, the MM5 model is being tested for use as a tool for integrating the field measurements of the Flux Study into regional estimates in a dynamically self-consistent fashion, using four-dimensional data assimilation (FDDA). A selection of results from all three phases, concentrating primarily on the BATS and LSM land-surface/vegetation representations, will be presented here.

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Recent Decreases in Arctic Summer Ice Cover and Linkages to Atmospheric Circulation Anomalies

James Maslanik[1] (University of Colorado-Boulder), Mark Serreze,[2] and Roger Barry[3]

Sea-ice data from November 1978 through September 1995 for the Arctic Ocean and peripheral seas indicate that summer ice coverage has been below normal in recent years, with extreme minima in 1990, 1993, and 1995. The net trend in summer ice cover over the 17-year period is -0.6% per year, with the extent of the perennial ice pack reduced by 9% in 1990–1995 compared with 1979–1989. The reductions are greatest in the Siberian sector of the Arctic Ocean. Linkages are proposed between these ice anomalies and a sharp increase since 1989 in the frequency of low-pressure systems over the central Arctic.

For further information about this work, see:

Maslanik, J.A., M.C. Serreze, and R.G. Barry. 1996. Recent decreases in arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophysical Research Letters* 23 (13): 1,677–1,680.

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Modeling the Coupled Arctic Ocean-Sea Ice-Atmosphere System—Ocean Circulation from New Results

Wieslaw Maslowski[1] (Naval Postgraduate School), Yuxia Zhang,[2] and Albert J. Semtner[3]

Features of the Arctic Ocean circulation are presented based on new results obtained from two high-resolution model runs:

1. 60-year integration using a massively parallel model of the Arctic Ocean, and
2. a five-year integration using a vector-parallel coupled Arctic Ocean/Sea-Ice model forced with 1990–94 ECMWF wind forcing.

The coupled model consists of the free-surface Semtner/Chervin global ocean model modified to the Arctic Ocean and the thermodynamic/dynamic ice model of Hibler (1979) improved for numerical efficiency by Zhang and Hibler (1997). The massively parallel ocean model is adopted from the global ocean version of Parallel Ocean Model (POP) developed by Los Alamos, NCAR, and Cray personnel for the Cray T3D. Two additional passive tracers were included in the ongoing simulation in order to better understand:

1. the horizontal and vertical spreading of waters entering the central Arctic through Bering Strait (by adding a source of silicate there), and
2. the dispersion of radionuclide pollution from the eastern Arctic (by introducing an idealized radionuclide tracer in the Kara Sea).

A massively parallel coupled Arctic Ocean/sea-ice model was recently constructed by coupling the existing ocean model to a massively parallel ice model developed by Maslowski and Zhang in collaboration with Craig (NCAR) from the original Hibler's model. This coupled model has been successfully tested using high frequency ECMWF forcing, and it is now being run using reanalyzed ECMWF multi-year winds and heat fluxes. It is also a very fast model capable of simulating one year in about 48 clock hours using 64 processing elements (PEs) of the Arctic Region Supercomputing Center (ARSC) Cray T3D/128 computer. Both model versions have almost uniform (due to the coordinate rotation) grid spacing of 18 km (*i.e.*, 1/6-degree) and 30 levels. The model domain includes the Arctic Ocean, Nordic Seas, Canadian Archipelago, and Subpolar North Atlantic. A free-surface model combined with the high resolution allows for the most accurate representation of the unsmoothed Arctic Ocean bathymetry in this model. Additionally, tidal forcing can be implemented into simulations if needed. Some results from the 60-year simulation including mean fields of kinetic energy, currents at different depth ranges, and passive tracer distributions are presented. Circulation of the Atlantic Water at a depth of 400 m is animated for the last 45 years of simulation showing near equilibrium model response to forcing used. Results from the parallel-vector and the massively parallel coupled models are shown. These results compare very well, which implies that a powerful coupled ocean-ice model exists for arctic system studies and 100-year simulations can now be completed in less than a year using high-performance computers.

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Major Features and Forcing of High Latitude Northern Hemisphere Atmospheric Circulation Over the Last 110,000 Years

Paul A. Mayewski[1] (University of New Hampshire), Loren D. Meeker,[2] Mark S. Twickler,[3] Sallie Whitlow,[4] Qinzhao Yang,[5] and Michael Prentice[6]

The GISP2 glaciochemical series (sodium, potassium, ammonium, calcium, magnesium, sulfate, nitrate, and chloride) provides a unique view of the chemistry of the atmosphere and the history of atmospheric circulation over both the high latitudes and mid-low latitudes of the Northern Hemisphere. Interpretation of this record reveals a diverse array of environmental signatures that include the documentation of anthropogenically derived pollutants, volcanic and biomass burning events, storminess over marine surfaces, continental aridity and biogenic source strength plus information related to the controls on both high- and low-frequency climate events of the last 110,000 years. Climate forcings investigated include changes in insolation on the order of the major orbital cycles that control the long-term behavior of atmospheric circulation patterns through changes in ice volume (sea level). Events such as the Heinrich events (massive discharges of icebergs first identified in the marine record) that are found to operate on a 6,100-year cycle due largely to the lagged response of ice sheets to changes in insolation and consequent glacier dynamics. Rapid climate change events (massive reorganizations of atmospheric circulation) are demonstrated to operate on 1,450-year cycles. The magnitude and potential for rapid onset and decay of these events appears to be related primarily to changes in insolation that affect the growth/decay of highly dynamic mediums such as ocean ice cover during periods of relatively extensive ice-sheet cover. Explanation for the exact timing and global syncroneity of these events is, however, more complicated. Preliminary evidence points to possible solar variability-climate associations for these events and perhaps others that are embedded in our ice-core-derived atmospheric circulation records.

For further information about this work, see:

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Energy and Water Vapor Fluxes Differ Among Vegetation Types in Alaskan Arctic Tundra

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Arctic land areas have the potential for globally important effects on climate because high latitudes are regions where current GCM scenarios predict the greatest greenhouse warming and because tundra soils contain large stores of carbon that could be released into the atmosphere. Our research focuses on the role of vegetation in the interaction between land and atmosphere in Alaskan arctic tundra. Our first question was whether tundra ecosystems differed strongly enough in the partitioning of the surface energy budget that they should be considered separately in models of regional and global climate. We used the eddy covariance technique to compare growing-season fluxes of energy and water vapor over different tundra ecosystems on the Alaskan North Slope. In this poster we summarize results from the 1994 field season, during which we measured fluxes in five of the major vegetation types that occur in the Alaskan Arctic. We found important differences in the partitioning of energy and water vapor fluxes over the range of tundra vegetation types we studied. As expected, the two extremes of the surface moisture gradient—dry heath and wet meadow—showed the largest absolute differences in water vapor fluxes. Sensible heat fluxes showed a trend opposite that of water vapor flux. The two tussock tundra sites, occurring on soils of intermediate moisture, had water vapor fluxes between these extremes and Bowen ratios close to 1. Overall, the fraction of net radiation going into latent heat flux closely followed the trend in soil moisture differences among our sites. Ground-heat fluxes ranged from 9–18% of net radiation at all except the wet meadow site, where mid-day ground heat fluxes exceeded 150 Wmã2. We attribute the large ground-heat flux values at this site to good penetration of radiation to the surface through the sparse vegetation, the very dark color of the organic mat that forms the soil surface, and the saturated condition. However, negative ground-heat fluxes during the arctic night also were large at the wet meadow site such that, overall, we saw very little variation among vegetation types in the ratio of ground-heat flux to net radiation on a net daily basis. Our most important finding was that there were substantial differences in energy and water vapor fluxes among three closely related vegetation types. The shrub, tussock, and mixed shrub-tussock tundra sites have broadly overlapping species composition and, because all naturally include some birch and willow shrubs, can be thought of as representing degrees of shrub relative dominance. The three sites all were located within <0.75 km of each other on one broad hill slope, and the shrub site was <6 percent different from the others in volumetric soil moisture, yet the partitioning of the surface energy balance was markedly different at the shrub site. Shrub tundra was the exception to the rule that energy and water vapor fluxes closely track soil moisture. The shrub site had the highest ratio of sensible heat to

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net radiation of all sites and a mid-day Bowen ratio slightly higher than the driest site we studied, heath. Energy partitioning in the mixed shrub-tussock vegetation was intermediate between the other two sites, but much nearer the tussock site. This result was contrary to our initial expectation that shrub tundra, which has the highest biomass and leaf area of all tundra vegetation types, would have relatively higher rates of latent heat flux compared to other ecosystems. We suggest that the important difference at this site is that the shrub canopy attenuates radiation reaching the surface and maintains a relatively low temperature near the ground, limiting evaporation from the most important source of water, wet mosses in the understory. This is consistent with the observation that ground-heat flux at the shrub site was the lowest of all sites we measured. Latent heat flux is further reduced at the canopy level by stomatal control. With little energy going into ground-heat flux and the shrub canopy limiting latent heat flux, the balance must be dissipated as sensible heat. Our major conclusions are:

1. Energy and water vapor fluxes differ among the major tundra vegetation types. Soil moisture content is the best indicator of differences in energy partitioning across a broad range of ecosystems.
2. Maximum rates of ground-heat flux show large differences in sites at the extremes of the moisture gradient, but net daily ground-heat fluxes were very similar among all vegetation types.
3. Plant growth-form composition (*e.g.*, relative proportion of shrubs and mosses in a community) can have important effects on ecosystem energy and water exchange.

These results suggest that conversion of tussock tundra to shrub tundra through shrub encroachment, which recent model studies and field experiments predict as a response to global warming in tundra, could result in rather different feedbacks to regional climate in comparison to the present vegetation.

The ARCSS Data Coordination Center at NSIDC: A Catalyst for Integration

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Scientific coordination and integration between each ARCSS component makes the ARCSS Program unique. The ARCSS Data Coordination Center at NSIDC encourages integration through several venues. Maintaining a focal point for data and information for the ARCSS Program is the main Data Coordination Center contribution for integration within ARCSS. Archiving and delivery of existing data, data product development, CD-ROM and ftp services, and information input into the Global Change Master Directory are primary methods to maintain an information and data management focus. Providing a wide variety of data and information access is another contribution toward integration. Access to the data holdings is achieved through direct contact with NSIDC User Services, direct login through anonymous ftp or via the ARCSS Home Page through the World Wide Web. We also work closely with each ARCSS component science steering committee and science management office to develop better strategies for information and data exchange throughout the ARCSS community.

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Storm Flow Dynamics in the Kuparuk River, Arctic Alaska

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POSTER PRESENTATIONS

A study is in progress in the Kuparuk River Basin in arctic Alaska to understand the hydrologic linkages between the terrestrial and aquatic environments in a regional arctic ecosystem. Such studies need distributed hydrologic information at scales much larger than the typical plot or headwater basin scales. One approach to address this scale disparity is to develop "scaling up" relationships that relate small-scale information to the larger scales of interest. Hence, we are interested in observing field hydrologic processes over a range of scales to provide empirical data upon which scaling relationships can later be tested. In this study we investigate the stream hydrologic response to storms in a nest of 4 basins within the Kuparuk River drainage. We present the results of hydrograph separation studies on storms during the summer of 1994 at 2 scales, then examine cross-scale relationships at 4 scales. Various techniques have been developed for partitioning storm hydrographs into source components. Traditional techniques involve graphical separation, or recession analysis, to determine the groundwater inputs into a storm hydrograph. In this technique, the shape of the hydrograph recession is used to decipher the timing and magnitude of surface and subsurface runoff. Newer, more physically based techniques separate hydrographs into source components using naturally occurring tracers. Assuming flow sources have distinctive chemical or isotopic signatures, simple 2-member mixing models are used to partition storm flow into "old water" and "new water" where old water is water that existed in the basin prior to a storm *(i.e.*, soil moisture and groundwater) and new water is the rain or snowmelt contributed by a storm. In this study we used specific conductivity as a tracer, and compare those results with graphical separation techniques. Numerous case studies using environmental tracers have shown that old water typically dominates storm hydrographs. The rise in stream flow due to a rain or snowmelt event is typically due to an increase in subsurface contributions to the stream, as opposed to surface runoff of new water into the stream. This can be thought of as a flushing effect where event water enters the soil and displaces soil water into the stream. The implications of large old water contributions to storm flow may have significant influences on terrestrial/aquatic interactions, specifically, the transport of nutrients from the terrestrial to the aquatic environment may be influenced by the hydrologic response of the basin. In this investigation, we suspected that the presence of permafrost in arctic environments may alter the "typical" storm response of large old water contributions. Hence, we are investigating how the surface and shallow subsurface interact in storm response as the ground thaws through a summer. Our results show that old water contributions to storm flow ranged from 60% to 81%, indicating that the hydrologic response is dominated by old water as is commonly found. An uncommon finding is that the old water contributions increased through the summer.

continued on next page

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Storm peak lag times between this headwater basin and the mouth of the Kuparuk River (drainage area = 8000 km^2) ranged from 3 days to 11 days. The proportion of storm flow at the mouth that was due to storm flow in the headwaters ranged from 4% to 11%. Lag times and headwater contributions showed similar seasonal trends to the old water contributions and increased through the season. We attribute these seasonal trends in hydrologic response to active-layer dynamics. These results suggest that the hydrologic and thermal regimes are tightly coupled.

For further information about this work, see:

McNamara, J.P., D.L. Kane, and L.D. Hinzman. 1997. Hydrograph separations in an arctic watershed using mixing model and graphical techniques. *Water Resources Research* 33 (7): 1,707–1,719.

Rovansek, R.J., L.D. Hinzman, and D.L. Kane. 1996. Hydrology of a tundra wetland complex on the Alaskan Arctic Coastal Plain, USA. *Arctic and Alpine Research* 28 (3): 311–317.

Scaling of River Flows in an Arctic Drainage Basin

James P. McNamara[1] (University of Alaska Fairbanks), Douglas L. Kane,[2] and Larry D. Hinzman[3]

A demand has been placed on hydrologists in recent years to quantify hydrologic fluxes at scales larger than those for which data is typically available. Hence, a critical area of research is the scaling and spatial variability of hydrologic processes. Research in temperate basins has shown that river flows obey multi-scaling as opposed to simple scaling. Essentially, simple scaling implies a constant coefficient of variation across all scales, and multi-scaling does not. Arctic river basins are underlain by permafrost. Consequently, the runoff generating mechanisms are considerably different than in temperate regions where most other scaling studies have been performed. We suspected that the small-scale differences in runoff generating mechanisms between arctic and temperate basins might produce differences in the scaling of river flows as well. We performed scaling analysis on three flow variables of 1994 hydrographs from 4 sub-basins ranging in drainage areas from 0.02 to 8,140 km^2 in the Kuparuk River Basin: 1) storm peaks, 2) inter-storm low flows, and 3) random flows. Further, we examined the differences in scaling of annual flood peaks between several arctic and Appalachian rivers. Our results show that flows in the Kuparuk River and flood peaks in arctic rivers exhibit simple scaling, whereas temperate basins exhibit multi-scaling. A possible explanation for the regional differences in scaling characteristics of river flows lies in the different natures of the hill-slope processing of precipitation inputs between permafrost and non-permafrost basins. Residence times in permafrost basins are short resulting in flashy hydrographs with quick recessions. Consequently, storms in tributary basins move through channel networks quickly and are thus less likely to overlap downstream with storm peaks from other tributary basins. Hence, the variability in stream flow will be maintained downstream. There is much more interaction with the subsurface in non-permafrost basins resulting in longer hydrograph recessions. Consequently, storm peaks from various tributary basins are more likely to overlap downstream. Hence, the variability will be smoothed downstream. These results illustrate the significance of permafrost in the functions of arctic ecosystems.

For further information about this work, see:

McNamara, J.P., D.L. Kane, and L.D. Hinzman. 1997. Hydrograph separations in an arctic watershed using mixing model and graphical techniques. *Water Resources Research* 33 (7): 1,707–1,719.

Rovansek, R.J., L.D. Hinzman, and D.L. Kane. 1996. Hydrology of a tundra wetland complex on the Alaskan Arctic Coastal Plain, USA. *Arctic and Alpine Research* 28 (3): 311–317.

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Nutrient Dynamics in Response to Storms in the Kuparuk River Basin

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As part of the ARCSS/LAII Flux Study, we implemented a study of nutrient dynamics in nested watersheds in the Kuparuk River Basin in arctic Alaska. Previous investigations have shown that nutrient concentrations in the Kuparuk River are low. However, no studies have attempted to relate nutrient concentrations to hydrologic events. We anticipated that hydrologically significant events including snowmelt and summer storms may impose patterns in nutrient loadings that may not be apparent in a routine weekly sampling scheme. We also suspected that storms may influence nutrient concentrations in streams in three ways. First, direct precipitation on the channels may provide nutrients from scouring of the atmosphere. Second, storms may flush relatively mobile nutrients from the soil and produce elevated nutrient concentrations in the streams. Third, storms may simply dilute nutrient concentrations in the streams. Further, we suspected that watersheds of different sizes may respond differently to storms. To address these problems we installed ISCO automatic water samples in three watersheds: the Upper Kuparuk River which drains 142 km^2, Imnavait Creek which drains 2.2 km^2, and a hill-slope water track which drains 0.02 km^2 in the Imnavait Creek basin. The autosamplers collected one liter samples every three hours through the summers of 1994 and 1995. During storms the bottles were subsampled for ammonia, nitrate, and phosphate then analyzed on an Alpchem autoanalyzer within 24 hours. During snowmelt, samples were collected twice daily. The highest concentrations for all species in each basin occurred during snowmelt. However, a few summer storms rivaled the snowmelt peaks. The volume of discharge during snowmelt is significantly greater than any individual summer storm which makes snowmelt the most significant nutrient loading event. During the summer storms there was little difference in the patterns of storm response between the different scales, but there were differences in the concentrations. Imnavait Creek and the water track had very low concentrations of nitrate and phosphate, but ammonia concentrations were similar at all scales. The following conclusions are general observations for all storms, but do not fit every storm. Each nutrient usually had an initial peak at the beginning of a storm. Ammonia concentrations appeared to follow precipitation patterns with concentration peaks at each precipitation peak and showed a general increase through the peak of a storm. This rise could be due to continual flushing of ammonia from the soil. Nitrate generally decreased through a storm after the initial peak. Because nitrate did not usually follow the precipitation peaks as closely as ammonia, it is likely that the initial peak is from an initial flushing of the soil and then is diluted through the rest of the storm. Phosphate was consistently low at all scales and only showed a small peak at the beginning of a storm.

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The Use of SAR Imagery to Predict Soil Moisture of the Kuparuk Watershed—Arctic Alaska

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The objective of this project is to investigate the potential use of satellite-borne Synthetic Aperture Radar (SAR) to measure near-surface soil moisture content over a large area in the Arctic. This distributed soil moisture data is needed to initialize and calibrate a spatially distributed hydrological model of the Kuparuk Watershed (8,140 km^2). Three SAR images obtained on June 21, 1995 were joined together to produce a mosaic of the study area. The mosaic was re-sampled to produce a ground resolution of 100 m. Terrain effects in SAR imagery make assessment of soil moisture levels difficult. Corrections were made to the raw SAR data to remove geometric distortion and radiometric distortion. SAR image geometric distortion may be divided into three categories: foreshortening, layover, and shadowing. Geometric distortions arise as a result of SAR signal transmission time difference between two points on the ground surface. The United States Geological Survey (USGS) has produced a Digital Elevation Data covering all of Alaska. Geometric correction involves relocating the pixels on the SAR image plane according to the Digital Elevation Data. SAR image radiometric distortion is a result of incidence angle variation. When the signal intersects the surface, some energy is reflected along a forward scattered direction, and some energy is back scattered to the signal source. A reduction in incident angle (*i.e.*, a radar signal illuminating a hill-slope facing the radar) produces greater backscattering and a resultant bright region, and conversely hill-slopes facing away from the radar signal would have a dark region. The backscattering intensity produced by varying incidence angles is not constant. A radiometric correction function produced by Goering *et al.* (1995) takes into account local incidence angle projected onto the range plane, angle between pixel normal vector and range plane, and the SAR incidence angle. Ground truth soil moisture data was collected in the field during the summers of 1993 and 1994. A computer-based neural network was trained using the measured soil moistures content, corrected SAR pixel values, and vegetation data. The corrected SAR images were analyzed in association with vegetation data (Auerbach and Walker, 1995) from the Kuparuk Watershed, utilizing a neural network to produce a calculated soil moisture map. Preliminary analysis shows that SAR data integrated with ground truth has the potential to be used to initialize and calibrate a spatially distributed hydrological model. Subsequent ground truthing is required to provide information necessary to train the neural network for ponds and nonacidic tundra, which as yet have not been monitored.

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Cesium-137 Contamination in Arctic Sea Ice

Debra Meese[1] (U.S. Army Cold Regions Research and Engineering Laboratory), Lee Cooper,[2] and I.L. Larsen[3]

Sea-ice and ice-borne sediment samples were collected across the western arctic basin on the joint U.S./Canada Arctic Ocean Section during August 1994. Samples were processed on board and returned at the completion of the cruise to Oak Ridge National Laboratory for analysis. Sediment was observed on the surface and in the ice from the southern ice limit in the Chukchi Sea to the North Pole. Preliminary results on the ice-borne sediment samples show widespread elevated concentrations of cesium-137 ranging from 4.9 to 73 Bq*kg dry weight-1. The lowest concentrations measured (4.9 to 5.6 Bq*kg dry weight-1) were found in samples on the Chukchi Sea continental shelf, and these concentrations correspond to activities reported for Chukchi Sea bottom sediments. The highest value (73 Bq*kg dry weight-1) found north of the Chukchi Sea, is comparable to elevated levels present in the shelf sediments of the Yenisey River estuary. By comparison, cesium-137 concentrations within the shelf itself (exclusive of sediment) were less than 1 mBq l-1, indicating that the ice was formed from seawater with substantially lower concentrations than sediments, or that contaminants are rejected in a manner similar to brine. These results indicate that sea ice is a primary transport mechanism by which contaminated sediments are redistributed throughout the Arctic Ocean and possibly exported into the Greenland Sea and North Atlantic through Fram Strait. The wide variability in the ice-borne sediment concentrations of cesium-137 measured along the transect argues that contaminants incorporated on the Siberian shelves can follow much more variable trajectories than is suggested by mean ice-drift calculations. Our findings strongly support future investigations of processes of radionuclide and sediment incorporation into ice. Likewise, modeling of ice transport from the Siberian shelves, as well as probability studies of ice trajectories derived from historical and current buoy drift fields are warranted to determine the fate of ice-transported radionuclides.

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Hydrology of a Small Arctic Coastal-Plain Wetland

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The Arctic Coastal Plain is a region of increasing human activity. Developments like the vast oil fields in Prudhoe Bay and the potential development of the Arctic National Wildlife Refuge can have significant impact on the fragile ecosystem and on the physical and biochemical processes of the Arctic. Better understanding of these physical processes is necessary in order to avoid any negative anthropogenic disturbances on this system. The Arctic is also a window to the global climate changes occurring on our planet; by monitoring the physical and biochemical processes in the Arctic we might have an insight to phenomena such as global warming and the greenhouse effect. With these objectives in mind, the hydrology of a small wetland complex in the Alaskan Arctic Coastal Plain is being studied to provide a better understanding of the role of water in the physical/chemical processes in the arctic wetlands. The 22.4 ha. study site named Betty Pingo is located in the North Slope of Alaska, inside the Prudhoe Bay oil field (see Figures 1 and 2). Within the Betty study site, there is a small watershed of approximately 8.15 ha. that is the focus of this study (Figure 2). Approximately 80% of the watershed is characterized as a jurisdictional wetland, containing numerous thaw ponds and strangmoor ridges. The remaining 20% is drier upland tundra, characterized by high-centered polygons and ice wedges. This poster presents results on snow ablation, runoff, and water-balance data collected at the Betty study site during a three-year period between 1993 and 1995.

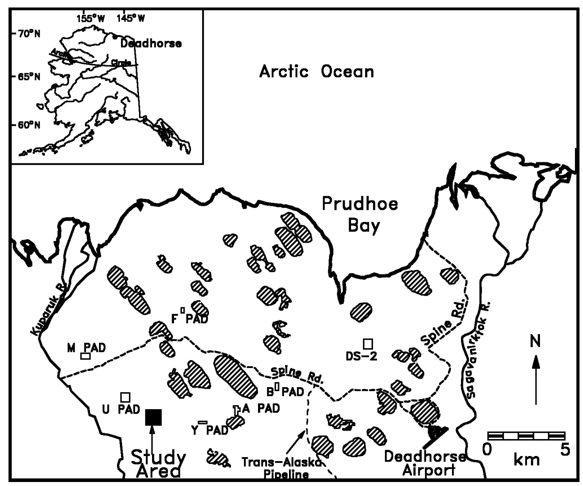

Figure 1. Prudhoe Bay oil field.

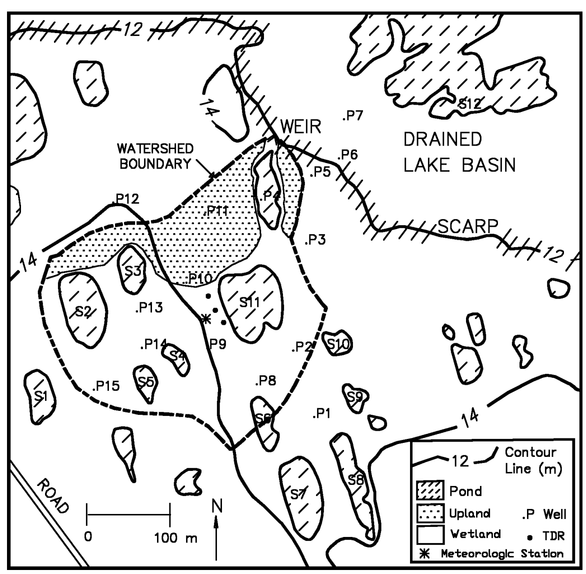

Figure 2. Betty Pingo study site.

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Carbon Storage and Distribution in Tundra Soils of Arctic Alaska

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A wide range of C stores (16–94 kgC/m^3) were observed for tundra soils (to 1 m depth). Lower C stores ranging from 3 to 10 kgC/m^3 were found in soils of the barren mountain slope, riparian shrub land, and alpine slope. Coastal plain soils averaged higher at 62 kgC/m^3 when compared to the foothills tundra at 44 kgC/m^3. The upper permafrost layers contained 11–77% of the total pedon C stocks. Soil morphology and carbon contents pointed to the importance of cryoturbation in the distribution of soil C stocks. Similar carbon stores (59–60 kgC/m^3) were observed for the center areas of polygon patterns studied on the coastal plain. In contrast, the C stores of coastal plain thaw-lake basin soils varied from 16 to 64 kgC/m^3. In the foothills region, carbon stores increased from ridgetop to watertrack positions, and increased or stayed nearly the same from mid-slope to water track positions. Carbon stock estimates doubled when considering the whole active layer compared to just the O and A horizons and then doubled again when stores to 1 m depth were considered. The Oa, Bg/Oa, and Cf horizons made the largest contribution to soil C stores (to 1 m). Kuparuk River Basin C store estimates (381 TgC) for 1 m were 2.5 times higher than those obtained using literature C store values.

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For further information about this work, see:

Michaelson, G.J., C.L. Ping, and J.M. Kimble. 1996. Carbon storage and distribution in tundra soils of arctic Alaska, USA. *Arctic and Alpine Research* 28 (4): 414–424.

Synoptic Climatological Aspects of Present and Past Climates of Beringia

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Surface climatic responses in Beringia are not expected to behave homogeneously as a single unit in the past, present, or future because of different synoptic circulation controls that operate within and adjacent to the region. This study analyzes the modern synoptic climatology of Beringia in order to identify the main synoptic circulation patterns that govern surface climate, and it also applies this information in assessing GCM (general circulation model) simulations and networks of fossil data for paleoclimates since the last glacial maximum. Composite difference maps of winter and summer temperature and precipitation illustrate that different synoptic patterns are clearly apparent when comparing the synoptic climatology of western Beringia with that of eastern Beringia, and some analyses illustrate the importance of topography for explaining spatial climatic variations at smaller spatial scales. Comparisons of GCM simulations with fossil pollen records, aided by modern synoptic climatic analyses, provide some explanations of spatial climatic variations for the last 18,000 years, with variations in the Aleutian low, Pacific subtropical high, East Asian trough, and Siberian high largely being responsible. However, some discrepancies are also apparent, perhaps as a result of some problems in the GCM simulations and the interpretation of fossil pollen data.

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The Terrestrial Record of Postglacial Vegetation and Climate from the Eastern Canadian Arctic and Western Greenland

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Pollen data from lake-sediment cores are available from many sites in Labrador and Greenland, but there are fewer sites in the northern islands. The region supports a wide variety of vegetation, from a closed boreal forest in southern Labrador to a rock desert barren in the far north, with intermediate zones of herb tundra, shrub tundra, and forest tundra. In southern and central Labrador, vegetation after deglaciation ca. 10 ka BP ranged from herb tundra in the north to birch shrub tundra in the south. By 8 ka BP, the vegetation was more dense as alder arrived and possibly spruce in low abundance. At 7 ka BP, fir arrived in the south, and at 5 ka BP spruce expanded over a large area in southern and central Labrador. North of Hudson Strait an open barrens was replaced by herb tundra on southern Baffin Island. Shrub tundra became more widespread at 6 ka BP with an increase in birch abundance and then many areas reverted to herb tundra at 4 ka BP. North of central Baffin Island the few sites available suggest a polar desert throughout the entire postglacial, with an increase in plant abundance in the early postglacial. Across Baffin Bay the period beginning at 7.5 ka BP is characterized by barrens in northwest Greenland. More favorable conditions after this time permitted the development of herb tundra in the north and shrub tundra in the south. A number of changes are indicated in the next 7 ka, but the regional coherence is difficult to determine due to steep gradients in vegetation and climate away from the coast and the high variability of local conditions. There is a deterioration in the last 3 ka in northwest Greenland.

For further information about this work, see:

Mode, W.N. 1996. The terrestrial record of postglacial vegetation and climate from the Arctic/Subarctic of Eastern Canada and West Greenland. *Geoscience Canada* 23 (4): 213–216.

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Estimation of Active-Layer Thickness Over Large Areal Units: Results from Kuparuk River Basin, Alaska

Frederick E. Nelson[1] (SUNY-Albany), Nikolai I. Shiklomanov,[2] Gerald Mueller,[3] and Kenneth M. Hinkel[4]

A general increase in the thickness of the seasonally thawed layer above permafrost could contribute to increased concentrations of atmospheric carbon. This study is concerned with modeling spatial variations of active-layer thickness over large areas containing complex patterns of topography, vegetation, and soil properties. The procedures are well adapted for use with climate-change simulations such as those being developed as part of the ARCSS research program. The study employed intensive field measurements of thaw depth made in a limited number of representative ground-cover categories, combined with temperature data collected at the same sites. GIS techniques were used analytically to merge these data with a digital elevation model, a digital vegetation map, and a topoclimatic index to produce an integrated map of active-layer thickness for the Kuparuk River Basin on Alaska's North Slope. Initial efforts at verifying the accuracy of the modeled values are encouraging. Mean values predicted by the model for the five 1 x 1 km ARCSS grids in and near the Kuparuk River Basin are in close agreement with those measured at the grids. A program of field measurements designed to test the model comprehensively will be implemented during the summer of 1996.

For further information about this work, see:

Nelson, F.E., N.I. Shiklomanov, G.R. Mueller, K.M. Hinkel, D.A. Walker, and J.G. Bockheim. 1997. Estimating active-layer thickness over a large region—Kuparuk River Basin, Alaska, USA. *Arctic and Alpine Research* 29 (4): 367–378.

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Permafrost Distribution and Active-Layer Thickness in the Northern Hemisphere Under Scenarios of Climatic Change: Results from Paleoreconstructions and General Circulation Models

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The proportion of the Earth's land area underlain by permafrost, currently about 25%, is expected to contract substantially in response to climatic warming. Maps of permafrost distribution in the Northern Hemisphere were generated using several general circulation models and an empirical paleoreconstruction, all scaled to a 2-degree global warming, in conjunction with a permafrost model that has successfully replicated the arrangement of contemporary permafrost zones in several high-latitude regions. The simulations indicate a 12–44% reduction in the total area occupied by equilibrium permafrost. Conditions specified by the climate models indicate a poleward displacement of all permafrost zones, although regional details produced by different models vary substantially. Transient GCMs generally produce smaller reductions in the extent of permafrost than do 2X CO_2 scenarios. Active-layer thickness increases are 20–30% in most locations, but approach 50% in some far northern locations.

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For further information about this work, see:

Anisimov, O.A., and F.E. Nelson. 1996. Permafrost distribution in the northern hemisphere under scenarios of climatic change. *Global and Planetary Change* 14 (1–2): 59–72.

Anisimov, O.A., and F.E. Nelson. 1997. Permafrost zonation and climate change in the northern hemisphere—results from transient general circulation models. *Climatic Change* 35 (2): 241–258.

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Unresolved Questions in Active-Layer and Permafrost Research for LAII

T.E. Osterkamp[1] (University of Alaska Fairbanks) and V.E. Romanovsky[2]

We will review recent research results and present our views on what are the current unresolved questions in active-layer and permafrost research in the Alaskan Arctic.

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Contemporary Water and Constituent Fluxes for the Pan-Arctic Drainage

Bruce Peterson[1] (Marine Biological Laboratory) and Charles Vorosmarty[2]

The Arctic is expected to exhibit strong responses to global change. This project examines the pan-arctic water balance with particular emphasis on spatially explicit estimation of freshwater export via rivers to the arctic coastal seas. Water balances will be quantified for the contemporary situation and annual variability from 1960 to 1990 determined. Water balance and river routing models will be combined with river constituent monitoring data to develop statistically based models of the fluxes of sediment and nutrients from watersheds to the Arctic Ocean. The timestep will be weekly at a spatial resolution of 50 km. The product will be a spatially explicit baseline of contemporary water and constituent fluxes from land to water for the entire pan-arctic drainage. This baseline is needed to assess the impacts of predicted climate change on pan-arctic water and nutrient balances. Societal impacts of changes in runoff and constituent fluxes include feedbacks to global climate change through alterations in sea-ice distribution and Arctic Ocean circulation as well as through impacts on the biotic resources of arctic wetlands, rivers, and coastal seas.

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Contaminant Transport Across the Arctic Basin by Siberian River Discharge and Kara Sea Ice

Stephanie Pfirman[1] (Columbia University), Stig Westerlund,[2] Jennifer Monteith,[3] Peter Schlosser,[4] Robert Anderson,[5] and Roger Colony[6]

River water discharged from the Siberian margin makes its way across the shelves and is caught up in the Transpolar Drift Stream. A front, centered at about 83°–84° N over the Gakkel Ridge in the western Eurasian Basin, separates surface waters influenced by river discharge to the north, from surface waters with little river influence to the south. Previous studies (Ostlund, 1994; Schlosser *et al.*, 1994; Bauch *et al.*, 1995) have shown that north of Svalbard and in western Fram Strait, river runoff comprises about 10% of the surface water, essentially representing a river flowing across the sea. Based on this distribution, it was predicted that conservative contaminants discharged by the Siberian rivers could have dilution factors as low as one order of magnitude by the time the water exited the Arctic Basin (Ostlund, 1994; Schlosser *et al.*, 1995). Comparison of the distribution river runoff and trace metals in the central Arctic Ocean shows that copper, and to a lesser degree nickel, appear to behave conservatively, both in the river estuaries (Martin *et al.*, 1993, Dai and Martin, 1995), and in the central Arctic. Their distribution is correlated with the fraction of river water in the surface ocean, and the extrapolated intercept at 100% river water approximates that of the river sources. Cadmium exhibits nutrient-like behavior and is strongly correlated with phosphate, as found in other ocean basins. Iron and lead appear to have a more recent source at the surface: a combination of atmospheric input and snow and ice melt. The concentration of metals in snow on the sea ice show that ice identified as coming from the Kara Sea carries a significantly increased contaminant load, most likely due to atmospheric deposition from Norilsk and other Eurasian sources. Comparison of values in snow with samples of ocean water at 0 m and 10 m suggests that melting snow may be responsible for contamination of the upper water column thousands of kilometers away, potentially influencing the region around Svalbard and the Barents Sea.

For further information about this work, see:

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Application of Stable Isotope and C-14 Dating to the Study of Soil Organic Matter Transformations in Arctic Soils

Chien-Lu Ping[1] (University of Alaska Fairbanks), Alexander Cherkinsky,[2] and Gary J. Michaelson[3]

The radiocarbon ages of 6 tundra soils from arctic Alaska were determined from the upper permafrost layers (Cf horizons) by conventional mass spectrometry (CMS). Soil organic matter (SOM) of the genetic horizons from one coastal marsh and one upland tundra soil was extracted with 1N NaOH followed by fractionation with the tandem XAD resin technique, then desalted and freeze-dried. The SOM was separated into humin (residue), humic acids (HA), fulvic acids (FA), low-molecular-weight acids (XAD-4 acids), hydrophobic neutrals (HON), and hydrophilic acids/neutrals (HIN). Except the HIN, all fractions were ^{14}C dated by Accelerated Mass Spectrometry (AMS). All radiocarbon data were corrected for $\partial^{13}C$= -25 0/00. The $^{13}C/^{12}C$ ratio was determined by CMS. The organic soil on the coastal marsh is characterized by high carbon content and a very slow rate of carbon turnover. Even the upper 18 cm (Oa1) has ^{14}C age of 700 years BP, the underlying horizons (O2&3) have 4,580, and Cf of 7,500 years BP. Modern ^{14}C age for residue organic matter or humin fraction in Oa1 horizon can be explained as the depletion of the relatively old organic matter due to extraction of humic and fulvic acids and enrichment by the young non-humificated organic matter. The increasing of ^{14}C age with depth is typical to peat deposits. In comparison, the profile from the upland tundra contains much less carbon and the amount decreases sharply with depth until the Cf horizon. The ^{14}C ages are also younger; from modern Oa and A horizons to 1,410 years BP in Cf horizon. The ^{14}C age of different fractions in this pedon are significantly younger than the same fractions in the coastal marsh profile. The rates of carbon turnover in the upland tundra soil are much faster than that of the coastal marsh. The ^{14}C age of the other 4 profiles ranges from 2,355 to 12,740 years BP. Such a discrepancy could be attributed to cryoturbation and gelifluction processes. In the surface horizon (Oa1) of the coastal marsh soil the $\partial^{13}C$ values of -29.1 of residual organic matter represents that of the fresh organic matter. In the lower horizons (Oa 2&3 and Cf) the residual organic matter represents the humin fraction and thus has the oldest ^{14}C age. The $\partial^{13}C$ value of the XAD-4 acids in the Oa2 and 3 horizon is -25.0 which is 4 0/00 lower than that of the modern organic matter. This is because of the anaerobic conditions in this horizon where more CH_4 was produced and thus there was an enrichment of ^{13}C. In the surface horizons (Oa and A) of the upland tundra soil, the $\partial^{13}C$ value and ^{14}C ages increase in the order of humic acids, fulvic acids, and XD-4 acids. Such a trend can be explained as evidence of enrichment of ^{13}C in the XAD-4 acids which are the end products of greater decomposition than the fulvic and humic acids. In summary, ^{14}C dating provides information in soil genesis, and the transformation of soil organic matter. Such information is only possible through detailed analysis of SOM from the whole soil profile.

For further information about this work, see:

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Morphological Characteristics of Permafrost-Affected Soils from Different Arctic Regions

Chien-Lu Ping[1] (University of Alaska Fairbanks), Gary Michaelson,[2] and John Kimble[3]

Recent studies indicate that arctic tundra soils have become a source rather than a sink for atmospheric carbon. With global warming the permafrost layer could release even more carbon. Characterization of cryogenic soils provides the carbon storage data base for arctic soils. From 1990 to 1994 a total of 70 pedons from selected areas of the circumpolar polar region were studied and described according to the Soil Survey (USDA-SCS) Manual. The results of these studies indicate that a modification of the existing Soil Survey Manual procedures for the examination and description of cryosols is necessary to accommodate cryogenic features. An appropriate arrangement of cryosols within the United States Soil Taxonomy is crucial to land-use interpretations and for environmental protection of the Arctic.

For further information about this work, see:

Michaelson, G.J., C.L. Ping, and J.M. Kimble. 1996. Carbon storage and distribution in tundra soils of arctic Alaska, USA. *Arctic and Alpine Research* 28 (4): 414–424.

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Two Arctic Ocean Circulation Regimes from Ocean Models and Observations

A. Proshutinsky[1] (University of Alaska Fairbanks) and M. Johnson[2]

Recent measurements in the Arctic Ocean and the inferred changes in circulation led Carmack and Aagaard (1996) to conclude that “remarkable new observations call for a revised conceptual model of the Arctic Ocean, and a re-thinking of theory and process parameterization.” Further, Morison (1996) reports that observational data “indicate a fundamental change in the circulation of the Arctic Ocean beginning in the early 1990s. It involves a shift of the front between the waters of the east and west, with a corresponding change in circulation and a warming of Atlantic Water.” In this paper, observational data are used to validate a numerical model showing the “typical” large-scale, anti-cyclonic circulation in the Arctic alternating with a cyclonic circulation pattern at a period of approximately ten to fifteen years. The major goal of this paper is to demonstrate and to confirm the existence of the two Arctic Ocean circulation regimes. Their existence may help explain the significant, basin-scale changes in the Arctic’s thermohaline structure observed during recent expeditions, the salinity anomalies observed in the Greenland Sea, and the variability of ice conditions in the Arctic Ocean in general. The model is two-dimensional, barotropic, with frictional coupling between the ocean and ice, and a spatial resolution of 55.5 km. It is driven by atmospheric forces, river runoff, and an imposed sea-level slope between the Pacific and the Atlantic oceans. The vertically averaged currents and ice drift in the Arctic Ocean have been simulated from 1946 to 1993. Comparisons between observed buoy and model buoy velocities are in good agreement. The model results show two wind-driven circulation regimes in the Arctic: an anti-cyclonic circulation is observed in the central Arctic during 1946–1952, 1958–1963, 1972–1979, 1984–1988, and cyclonic circulation is observed during 1953–1957, 1964–1971, 1980–1983, and 1989–1993. Each regime appears to exist for 5 to 7 years, forced by changes in the location of the atmosphere’s polar lows and highs. The atmosphere also drives quasi-oscillations in the model circulation at shorter periods of 2 to 3 and 5 to 7 years. It is hypothesized that the 10–15 year oscillation in the Arctic Ocean is driven by North Atlantic Oscillation through the strengthening of the Gulf Stream and resulting northward penetration of Atlantic Water into the Arctic Ocean. A 2–3- and 5–7-year oscillation is generated by the adjustment between atmosphere and ocean in the Arctic.

For further information about this work, see:

Proshutinsky, A.Y., and M.A. Johnson. 1997. Two circulation regimes of the wind-driven Arctic Ocean. *Journal of Geophysical Research* 102 (C6): 12,493–12,514.

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Understanding of Interdependence of Atmospheric, Oceanic, and Terrestrial Processes in the Arctic System

A. Proshutinsky[1] (University of Alaska Fairbanks), M. Johnson,[2] V. Romanovsky[3], and T. Osterkamp[4]

The poster will include the following topics:

1. Data showing cycles in atmospheric, oceanic, and terrestrial processes and results of their modeling. Questions need to be solved.
2. Hypotheses explaining mechanism of cyclicity (self-regulated arctic system or arctic system driven by external forces).
3. Moving toward integrated arctic system model and proposals for numerical experiments.

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Volume Changes of McCall Glacier, Alaska and Date of Seasonal Snowmelt on Alaska's Arctic Slope in Response to Climate Warming in the Arctic

Bernhard Rabus[1] (University of Alaska Fairbanks), Keith Echelmeyer,[2] and Carl S. Benson[3]

Research on McCall Glacier in the northeast part of the Brooks Range began in 1957 during the International Geophysical Year (IGY). Comprehensive measurements included glacier mass balance studies and a detailed photogrammetric, topographic map of the glacier. After a ten-year gap, the Geophysical Institute of the University of Alaska renewed research in 1969. The current LAII project extends and broadens the research on McCall Glacier and on adjacent glaciers in this region. Detailed cross sections of the McCall Glacier, made in 1969, '72, '75, '87, and '93, show a dramatic loss of mass. The rate of mass loss increased in about 1977; this is consistent with increases in temperature recorded at most Alaskan meteorological stations. The well-documented mass loss of McCall Glacier extends throughout the glacier. Measurements on ten other glaciers in the region show similar net mass losses, although detailed studies of the rates of change are not available. Seasonal snow on the Arctic Slope has been studied since 1962. The studies have been done in greatest detail at Imnavait Creek, near Toolik Lake, during the period 1985–1995. The rate of snowmelt is roughly the same each year. Once it is seriously underway, the snow is gone within about ten days. However, the time that the melting takes place is randomly distributed over a period of six weeks. It is not possible to see a trend toward earlier snowmelt with time because of the "six-week noise" in the phenomenon. In contrast to the time of snowmelt, with its noisy signal, mass changes of the glaciers show an integrated response to the changing climate with "low noise." With the existing base of information, simple monitoring of glaciers in the Brooks Range can provide a clear and unequivocal response to the current climate warming in the Arctic.

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An Estimate of Methane Emission for the Kuparuk River Region

S.K. Regli[1] (University of California Irvine), W.S. Reeburgh,[2] and J.Y. King[3]

This poster summarizes two field seasons (1994 and 1995) of approximately semiweekly net CH^4 flux measurements at sites representing the major land-cover classes of the Kuparuk River Basin, Alaska. Flux data was integrated over the thaw season, and means and ranges were determined for each land-cover class. This data was then used with a Landsat-derived vegetation map to show a spatial depiction of methane fluxes in the region. In total, 21 static chambers were set up at Toolik Lake and 10 chambers at Happy Valley. They encompassed the classes of: (1) moist nonacidic tundra, (2) moist acidic tundra, (3) shrub lands, (4) wet tundra, and (5) barrens. Annual emissions estimates were determined for each of the six regions of the map.

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Laminated Lacustrine and Marine Sediments from Sophia and Depot Point Lakes, Eastern Cornwallis Island, Canada: Contrasting Styles of Sedimentation in Coastal Lowland Basins and Implications for Paleoenvironmental Reconstruction

Michael Retelle[1] (Bates College) and Alex Robertson[2]

The annual-to-seasonal resolution of varved sediments and their wide occurrence in lakes across the Arctic provide regional extension to the highly detailed records recovered in high-latitude ice cores and dendrochronological records found at treeline. However, before a reliable paleoclimatic interpretation of the laminated lacustrine records can be made, a thorough understanding of the controls and processes that operate and control sedimentation in individual basins must be understood. Recent work has been conducted on two coastal lake basins on the east coast of Cornwallis Island, N.W.T. that were recently isolated from the adjacent sea by glacioisostatic emergence. Both lakes contain finely laminated sediments, however, the styles and rates of sedimentation in these adjacent basins are quite different despite having similar bedrock source and catchment size. Sophia Lake is a hypersaline meromictic lake with anoxic basal waters up to 58 parts per thousand. The lake, at 4 meters above sea level, emerged ca. 1,000 years BP from the adjacent sea due to glacioisostatic emergence of the coastline. The drainage basin of the lake is approximately 75 km^2. Laminated lacustrine sediments comprise only the upper 1.5 to 15 cm above the massive marine sediment deposited when the basin was a marine inlet. In general, laminated sediments consist of thin laminae that include several types. Thin sediment couplets consist of a basal clastic unit of silt and fine sandy silt overlain by a paper thin silt/clay layer. In the central basin of the lake individual couplets range in thickness from 0.1 to 0.5 mm (Mean = 0.21 mm; s.d. 0.11). Thicker laminae include numerous turbidite layers up to 3.8 mm thick which exhibit either a massive or fining-upward, graded bed structure. Hydrological and sediment flux monitoring at Sophia Lake throughout the 1994 summer season recorded minimal suspended sediment transport to the basin and suggests that the carbonate bedrock source and an up-basin sediment trap limited and restricted the amount of sediment available for transport to Sophia Lake despite sufficient snowmelt runoff to transport a suspended sediment load (Hardy *et al.*, this volume). Depot Point Lake, situated approximately 15 km south of Sophia Lake is presently a freshwater lake at approximately 7 meters above sea level and a catchment of 82 km^2. The laminated sediments comprise the entire length of the core recovered from the eastern or distal portion of the basin. Individual laminated couplets average approximately 1 mm thick with numerous turbidite layers 1 cm thick or greater. The structure of the laminated couplets resembles those of classic clastic varves with well-defined “summer” layers with multiple-graded laminae representing individual flow events, and a structureless “winter” layer of fine-grained mud. Research in summer 1996 will focus on recovery of a suite of cores from Depot Point Lake where it appears that apparently a clear, resolvable, and long-term sedimentological signal is preserved in the laminated sediments. In addition seasonal sediment traps will be deployed in the lake to monitor sediment flux over several seasons.

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Temporal and Spatial Dynamics of the Active-Layer and Near-Surface Permafrost on the Coastal Plain of Northern Alaska

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Spatial and temporal variability of the air, ground, and permafrost temperatures were analyzed using daily temperature data (upper 0.9 m) from 1986–1993 and results of annual temperature measurements in boreholes (nominally 60 m) from 1983–1995 at three sites in the Prudhoe Bay region of Alaska. 1993–1994 ground temperatures at Barrow, Alaska also were used. Numerical calculations were used to estimate the interannual variability of the thermal properties of soils which appear to be a result of interannual variations of the average water content during the summer in the upper part of the active layer. Precise temperature data together with computer modeling provided essential new information on dynamics of unfrozen water content in the ground in natural undisturbed conditions during freezing and the subsequent cooling of the active layer. A layer with unusually large unfrozen water content was found to exist at the depth of freeze-up. The same set of data was used to reconstruct daily permafrost temperatures from 1986–1995 for all depths down to 55 m. Mean annual temperature profiles for each year of 1987–1995 show significant interannual variations.

For further information about this work, see:

Osterkamp, T.E., and V.E. Romanovsky. 1996. Characteristics of changing permafrost temperatures in the Alaskan Arctic. *Arctic and Alpine Research* 28 (3): 267–273.

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Isotope Tracers of Climate in Arctic Lake Waters and Sediments

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By measuring proxies of climate in lake sediments, it is possible to develop continuous records of environmental change. Because lakes are ubiquitous in glaciated areas, lake-sediment studies can provide climate records for virtually any part of the terrestrial Arctic, enabling us to study both spatial and temporal aspects of the arctic climate history. The most detailed picture of the development of arctic climate will use a wide distribution of sites and many different proxies because each proxy has a different sensitivity to environmental variables. We have analyzed water, vegetation, and surface sediment samples from >150 lakes distributed across sharp gradients of mean annual temperature and in precipitation. In cold parts of the world, there is a strong correlation between mean annual temperature and stable isotopes of oxygen and hydrogen in precipitation (Dansgaard, 1964). For the most part, the stable isotope ratios in lake water bear the same relationship to temperature. Because evaporation from lakes causes isotopic enrichment of the lake water, it is possible to use isotope ratios to estimate evaporation and other parameters in the hydrologic cycle. These estimates of temperature, evaporation, and precip/evap ratios may be combined with climate model output to better understand the arctic system. Analysis of sediments from six lakes from the eastern Canadian Arctic provide a picture of Holocene climate change. Although each record is incomplete, together they support a coherent model, showing postglacial warming, an early Holocene period of maximum warmth, and cooling at 4–6 ka.

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A Tracer Study of the Circulation in the Arctic Ocean

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During the past 8 years, we collected an extensive tracer data set from all major basins of the Arctic Ocean (Nansen Basin, Amundsen Basin, Makarov Basin, and Canada Basin). The data have been used to study the deep water formation and exchange rates in the Greenland, Iceland, and Norwegian seas and the Arctic Ocean, as well as the mean residence times of the individual water masses observed in this region. In this poster, we present examples of the results obtained so far for these studies. For example, information on circulation patterns and mean residence times of the individual water masses begin to emerge. Mean residence time for shelf water is ca. 3 years, surface and halocline waters ca. 5 to 10 years. Intermediate and deep waters have mean residence times of several decades to 100 years. Mean isolation ages are ca. 250–300 years for Eurasian Basin deep water and ca. 450 years for the deep bottom waters of the Makarov and Canada basins. Continuing studies will reveal details of Arctic Ocean circulation. In addition, we started to use tracer data to calibrate Arctic Ocean models.

For further information about this work, see:

Schlosser, P., B. Kromer, B. Ekwurzel, G. Boenisch, A. McNichol, R. Schneider, K. von Reden, H.G. Ostlund, and J.H. Swift. 1997. The first trans-arctic C-14 section—comparison of the mean ages of the deep waters in the Eurasian and Canadian basins of the Arctic Ocean. *Nuclear Instruments and Methods in Physics Research Section B* 123 (1–4): 431–437.

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Applications of a Single-Column Ice/Ocean Model to Understanding the Sea-Ice Mass Balance

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The Arctic Ocean sea-ice mass balance is of fundamental importance to arctic and global climate. However, sea ice is crudely represented in present climate models. To provide a systematic framework for incorporating improved physics into the sea-ice parameterizations used in climate models, a single-column, dynamic/thermodynamic-ice/ocean model has been developed. An attempt has been made to combine all of the features presently used in the most sophisticated 2-D ice dynamics models with those used in the most sophisticated 1-D thermodynamic models. The model includes ice export, ridging, ice-thickness distribution, spectral-radiative transfer, ice age, melt ponds, lateral melting in leads, and frazil-ice production. Only by including all significant physical processes in a detailed model can rational decisions be made for the elimination or simplification of a specific process for climate model parameterizations. Details of the mass balance of first-year ice, multi-year ice, and ridged ice are presented, including basal accretion/ablation, evaporation/sublimation, melt runoff, and aging. The model results are compared with observations from drifting ice stations Alpha and Charlie. Sensitivity of the ice-mass balance to several physical processes is included. Recommendations are made for essential features to be included in a sea-ice parameterization for climate models.

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Transient Tracer Evidence for Circulation of the Barents Shelf Branch of Atlantic Water Along the Continental Slope of the Laptev Sea

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During the summer of 1993 two oceanographic sections were taken across the continental slope region of the Barents Sea and four across the continental slope region of the Laptev Sea on the Polarstern Ark IX/4 cruise. Hydrographic and transient tracer (chlorofluorocarbon, tritium, and He-3) data clearly reveal two branches of Atlantic water, the Fram Strait Branch and the Barents Sea Branch, flowing into the Arctic Ocean, as proposed by Rudels *et al.* (1994) and confirmed by Schauer *et al.* (1997) using the hydrographic data from the Ark IX/4 cruise. Along the Barents Sea slope, the Fram Strait Branch is 20–30 km seaward of the shelf break and has a tritium/He-3 age of 2–3 years. In the Laptev Sea region, the Fram Strait Branch has mixed with and been displaced by the Barents Sea Branch and its core is 100 km or more seaward of the continental slope. It has a tritium/He-3 age range of 6–7 years. The Barents Sea Branch enters the Arctic Ocean from the Kara Sea region and is clearly evident along the Laptev slope as a layer of low-salinity, high-tracer water between 300 and 1,100 m extending about 100 km seaward from the continental slope. Lateral maps of hydrographic and tracer properties on the core density surface of the Barents Sea Branch show a plume of cold, fresh, high-tracer water flowing along the isobaths of the Laptev slope. The average tritium/He-3 age of the Barents Shelf Branch along the Laptev slope is about 5.5 years and there is a clear increase in age of about 1 year between 110 and 135 degrees E. This age increase corresponds to an apparent current speed of about 1 cm/sec and a volume transport of about 0.7 Sv.

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Development of an AVHRR-NDVI Regional Carbon Flux Model and the Spatial Variability of Arctic Tundra Landscapes in Relation to CO_2 Flux

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Carbon flux data collected at sites on the coastal plain and foothills of the North Slope of Alaska using flux chambers were used to develop the following models: GPP/PAR = f(NDVI), and R = f(NDVI, Tair), where GPP = gross primary production, PAR = incident photosynthetically active radiation, R = ecosystem respiration, Tair = air temperature (all quantities were daily averages) and NDVI = the normalized difference vegetation index. The red and near-infrared reflectances required to calculate the NDVI were measured using a hand-held radiometer and halon calibration panel. This poster describes a procedure for making regional estimates of GPP and R using spectral radiances from the NOAA Advanced Very High Resolution Radiometer (AVHRR) to calculate the NDVI and the carbon flux models described above. The approach requires that the chamber scale models be tested using data collected at the scale of eddy correlation towers and along transects where fluxes and reflected spectral radiances have been measured from a light aircraft. Scaling AVHRR-NDVI values to be consistent with the hand-held radiometer values is central to the research effort. The approach is demonstrated using AVHRR data collected on August 17, 1994 to calculate carbon fluxes for the Kuparuk River Basin. Spatial patterns of PAR and Tair for the basin were obtained from the Kane and Hinzman hydrology-climatology study and used with the scaled AVHRR-NDVI values to calculate GPP and R. Net ecosystem exchange of carbon (NEE) was estimated as the difference between these two flux values. Patterns of GPP, R, and NEE over the Kuparuk Basin are presented. We also examined the spatial variability of land-cover types (grouped according to CO_2 functional relationships) and NDVI at and between the SPOT-HRV and NOAA-AVHRR satellite observation scales. Three general flux regimes are evident at all spatial scales along the transect: wet coastal plain, moist foothill, and transition zone. The major influence on the scaling relationship between SPOT-HRV and NOAA-AVHRR is the relative importance of inorganic surfaces contributing to the satellite signal. SPOT-HRV data provide a means for quantifying the proportion of surface water and other nonvegetated cover within NOAA-AVHRR pixels to normalize the NDVI to CO_2 flux relationship.

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LAII Snow Distribution Studies

Matthew Sturm[1] (U.S. Army Cold Regions Research and Engineering Laboratory-Alaska), Glen Liston,[2] Jon Holmgren,[3] Max Koenig,[4] Bert Yankielun,[5] and Carl Benson[6]

Tundra snow consists of primarily two snow components, depth hoar and wind slab. Depth hoar is often preferentially located between tundra tussocks, where the initial slab snow was less dense or hard. The thermal conductivity of depth hoar (approx. 0.05 W m-1 K-1) is 1/4 to 1/10 that of the wind slab. The insulation value of both depth hoar and wind slab can be estimated from regressions published by Sturm *et al*. (1997), but the relative percentage of depth hoar varies in an irregular manner over the Kuparuk Basin making spatial estimates of snow thermal resistance difficult. On the scale of tens to hundreds of meters, tundra snow is transported and relocated by the wind. Two types of drifts form: those that fill and those that do not fill. The latter form in the lee of large bluffs or in large river cuts. They can be used to estimate the annual wind-blown flux of snow: drift volume can vary by a factor of six from one winter to another. Both filling and non-filling drifts can be modeled. The empirical model of Tabler (1975) gives good results but requires local calibration. The physical model of Liston *et al*. (1993) can be used in any location, but requires detailed meteorological input and is computationally intensive. Neither model has been applied to large areas, but could be. In the Kuparuk Basin, snow-depth and snow-water equivalent (SWE) decrease with increasing latitude. Depth decreases monotonically from the Brooks Range to the Arctic Coast, but SWE shows a step-change at the coastal-upland boundary. This is the result of distinct differences in coastal and upland snow densities. Within the uplands subregion near the Brooks Range, valley bottoms contain deeper, less dense snow, with greater local depth variability than is found on broad ridge tops. On the coastal plain, snow on lakes tends to be thinner but denser than the surrounding snow. Semivariograms based on 21 stations located between the coast and the Brooks Range (depth and elevation data from 100 m lines at 10 cm spacing) indicate a distinct difference between coastal and upland snow at smaller (<100 m) scales. Coastal snow is so thin as to just fill the depressions between tussocks, creating a smoother surface than the underlying tundra, while upland snow is sufficiently thick that the development of sastrugi creates a snow surface that has surface undulations with greater amplitude (but also longer wavelengths) than the underlying ground surface. Variations in the snow depth distribution affect heat flow from tundra tussocks (Sturm and Holmgren, 1994), and also affect the entire snowmelt process (Liston, 1995). Using measured values of snow depth and general knowledge of the snow-landscape-vegetation interactions, a snow-depth map for the Kuparuk Basin has been developed. From this preliminary map, a sampling scheme for the 1997 field season has been implemented that will allow us to resolve east-west, as well as north-south, depth gradients.

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A physically based snow transport model has also been developed and is currently undergoing testing using dense spatial data from Imnavait Creek. Ultimately we will use both approaches to develop snow maps of other areas.

For further information about this work, see:

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PALE Climate Model Simulations for 21 ka, 10 ka, 6 ka, and Present Using the NCAR GENESIS Version 2 Climate Model

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In support of the Paleoclimates from Arctic Lakes and Estuaries (PALE) research program, we are performing a series of global paleoclimate simulations using the new version 2.0.a of the NCAR GENESIS climate model. Our objective is to examine the broad spatial changes in arctic/ boreal climates resulting from the relatively slow changes in major boundary conditions. To date, we have performed four simulations for the time periods 21 ka, 10 ka, 6 ka, and Present (calendar years). These times were chosen, respectively, to approximately represent: the last glacial maximum; a time when the Laurentide ice sheet was still present, but smaller; a time of relative Holocene warmth; and today. The extent and height of the ice sheets were prescribed (Peltier, 1994), as were greenhouse gas concentrations. Sea-surface temperatures and sea-ice concentrations were simulated by a simple-slab, ocean-mixed layer model with the ability to simulate the dynamics and thermodynamics of sea ice. The type and properties of the surface vegetation was interactively modeled using the Equilibrium Vegetation Ecology (EVE) model, which predicts the equilibrium state of natural vegetation as a function of climate. We will discuss the results of these simulations in terms of surface-temperature effects and atmospheric circulation patterns. In particular, we will examine whether the large spatial and time-scale patterns of change seen by PALE investigators is reflected in the simulations.

For further information about this work, see:

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Stable Tritium History in the Eurasian Basin

Zafer Top[1] (RSMAS)

A number of tritium/Helium-3 surveys were made in the Arctic Eurasian Basin since 1979: LOREX (1979), FRAM III (1981), MIZEX83 (1983), MIZEX84 (1984), NEWP (1993). A summary of these measurements was made to examine the variation of stable tritium in the near-surface, atlantic, and deep layers of the Eurasian Basin. The emerging pattern suggests that the deep waters had been renewed (if at all) at a reduced rate since the early 1980s. This conclusion is consistent with the results of the time series observations in the central Greenland Sea, made in the 1980s.

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Contributions to GISP2 Paleoclimate from Ice Sheet Geophysics

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The GISP2 and GRIP ice cores in central Greenland have provided paleoclimate records of unprecedented quality covering more than the past 90,000 years. Geophysical surveys and ice-dynamics programs played an essential role in choosing the most appropriate sites to get these high-quality records. Key components were the airborne ice-penetrating radar survey, the regional snow accumulation survey, and modeling predictions of expected depth-age scales and basal ice temperatures. The drillers were able to proceed knowing the thickness of ice to drill. The ice-core geochemists had confidence beforehand that the oldest ice had not been removed by basal melting, and climate record from occluded gases would be preserved in the ice over the complete depth of the ice sheet. Geophysical methods also provided estimates of the two most fundamental paleoclimate parameters independent of the geochemical records in the ice cores. First, temperatures deep in the boreholes "remember" the climate temperature at the ice-sheet surface in the distant past, so that geophysical temperature logging programs in the deep holes allowed the stable isotope proxy temperature history to be corroborated. Indeed, the isotope temperature record must be calibrated by borehole temperature logs at each site. Second, geophysical ice-flow modeling determined the amount of thinning that each observed annual layer had undergone as a result of ice flow, so that paleo-accumulation rates could be derived from the measured annual layer thicknesses in the ice core. Ongoing geophysical borehole logging and ice-

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dynamics modeling are revealing much about the way the ice-sheet environment has changed during the epoch covered by the ice-core paleoclimate record, and identifying causes of the stratigraphic disturbance disrupting the record in the bottom 10% of the ice sheet. A comprehensive geophysics program to choose the best site, to predict the depth-age scale, and to provide key independent paleoclimate variables, should be an integral part of every ice-coring program.

A Hierarchic GIS for Studies of Process, Pattern, and Scale in Arctic Ecosystems: The Arctic System Flux Study, Kuparuk River Basin, Alaska

D.A. Walker[1] (University of Colorado-Boulder), Nancy A. Auerbach,[2] Leanne R. Lestak,[3] Stephen V. Muller,[4] and Marilyn D. Walker[5]

The Arctic System Science (ARCSS) Program is part of the U.S. Global Change Research Program. The Land-Atmosphere-Ice Interactions (LAII) Flux Study, a component of ARCSS, is a multi-university effort to examine fluxes of trace gases, energy, and water to better understand arctic land-atmosphere linkages (Weller *et al.*, 1995). The study focuses on the Kuparuk River Basin in northern Alaska, with two main goals:

1. a quantitative understanding of the variables and processes controlling the fluxes of CO_2 and CH_4 from arctic ecosystems to the atmosphere and ocean, and
2. a determination of how these fluxes will change in response to future variations in climate and the arctic system.

Detailed and accurate geographic information is needed at a variety of scales in order to determine the spatial variability of key ecosystem processes that are important to arctic land-atmosphere interactions, biogeochemical fluxes to the Arctic Ocean, arctic biodiversity, and the response of plants and ecosystems to human-induced changes. The hierarchic geographic information system (HGIS) is designed to address a wide variety of questions ranging from plant-level responses to the global distribution and function of tundra ecosystems. The HGIS is being used to translate the findings from the plot-level investigations to regional and global scales. When completed, the GIS will allow comparative studies at six scales (plot-level, 1:10 scale; landscape-level, 1:500 and 1:5,000 scales; regional-level, 1:25,000 and 1:250,000 scales; and global-level 1:5,000,000 scale). We focused on the foothills of the upper Kuparuk River Basin during the first phase of the program; another similar hierarchy of databases is planned for the Prudhoe Bay region. This poster (4 panels) portrays some of the questions being addressed at the plot to regional levels of the HGIS. The first panel presents the conceptual framework of the HGIS, and describes the hierarchic vegetation classification and the hierarchy of digital elevation models. Panel 2 is devoted to plot-level issues and describes a unique GIS data set associated with small permanent plots placed at the grid points of 1 x 1-km research grids. These detailed observations are being used to address a variety of questions related to plant species response to site factors, climate change, and anthropogenic disturbances. Panel 3 describes two landscape-level databases that focus on issues related to movement of water and materials along topo-sequences and small watersheds. The panel describes the GIS at the Imnavait Creek site that have been instrumental in developing a wide variety of models that predict arctic ecosystem response to environmental variation and disturbance (*e.g.*, Oechel, 1989; Reynolds and Tenhunen, 1996). Panel 4 describes two regional-level databases that enclose the upper Kuparuk River and entire Kuparuk River Basin. These databases address topics related to fluxes over very

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large areas and long-term response of arctic ecosystems to climate change, including: linkages between the land surface and the atmosphere, flux of water, dissolved organic carbon, and nutrients to the Arctic Ocean, and regional-scale disturbance patterns. Applications are also presented at each scale including: a derived soil carbon map (Walker *et al.*, 1993), output from topographically derived vegetation models (Reynolds and Tenhunen, 1996, Ostendorf *et al.*, 1996, Leadley *et al.*, 1996) a SPOT-derived biomass map (Shippert *et al.*, 1995), effects of landscape-age on spectral patterns (Walker *et al.*, 1995), and an active-layer map for the Kuparuk River Basin derived to topographic, geobotanical, and climate data (Nelson *et al.*, 1997).

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Particle Dynamics and a Conceptual Model of the Inferred Flow Field of the Northeast Water Polynya

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Profiles of beam attenuation during the Northeast Water Polynya project in 1992 and 1993 reflect a combination of bathymetric control of the flow field and biological processes. The study area comprised the northeastern shelf off Greenland from roughly 75° N to 81° N. The bathymetry in the area consists of a series of linked troughs (Belgica, Norske, and Westwind troughs, south to north) surrounding Belgica Bank. To the east is the shelf edge and the East Greenland Current (EGC). To the west and north lies a shallow bank (Ob Bank) and Greenland. During the summer, the polynya develops as ice flows are swept to the north and east, with replenishment from the south inhibited by a wedge of fast ice extending over the Norske Trough from Greenland to Belgica Bank. Analysis of the beam attenuation profiles indicates that the northeastwardly flowing water in the Norske Trough impinges on the northwest side of the Norske Trough, resuspending sediments and forming an intermediate nepheloid layer. Past the constriction between Belgica Bank and Greenland, flow separation forms a tightly constricted counterclockwise eddy on the northern side of the main flow, and a larger clockwise eddy on the southern side of the flow. Near the saddle point between the Westwind and Norske troughs the flow impinges on the bank, resuspending sediments and altering direction such that the flow switches from the northern side of Westwind Trough to a southeastward flow along the southern flank of the Westwind Trough. In the surface water, the flow emerging from under the ice wedge into the ice-free zone of polynya drives a light-limited, eutrophic production regime. By the time the water mass enters the Westwind Trough, oligitrophic conditions have developed where light is not limited (*i.e.*, in the ice-free zone of Westwind Trough). As the water mass swings toward the south and west onto Belgica Bank, the ice cover over the bank limits insolation and, hence, production, resulting in low particle concentrations in the surface layer. Some of the resulting surface water mass on Belgica Bank, relatively depleted in nutrients and containing few particles, passes across the shallowest western part of Belgica Bank, mixing with the northward flowing.

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International Tundra Experiment (ITEX) Activities at Barrow, Alaska: Initial Short-Term Responses to Growing Season Warming

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During the summer of 1994 the International Tundra Experiment (ITEX) standard warming experiment was established on a dry-ridge site at Barrow, Alaska (71°19' N, 156°37' W). In 1995 the experiment expanded to include a wet-meadow site. In ITEX information is gathered about the response of tundra plants to the projected warmer arctic climate. It is designed to be a simple, low-cost experiment which can be placed in remote sites around the Arctic. There are now 26 circumpolar ITEX sites in 11 countries. This also permits the study of spatial and temporal variation of summer climate and plant responses. The standard basic experiment at each ITEX site uses small (1.5 m^2), passive, clear plastic, open-top chambers (OTCs) as greenhouses to raise the temperature of the plant canopy. It is postulated that accelerated phenology, increased growth, and changes of vegetation composition will occur within the chambers. Twenty-four OTCs and the same number of control plots were established at each site. Here we report preliminary results of OTC performance and plant response from the Barrow sites. The response of the circumpolar ITEX species *Cassiope tetragona*, *Eriophorum triste*, and *Carex stans* and all other species contained in the chambers were monitored. The temperature within the OTCs throughout the monitoring period was found to be on average 1.7° C warmer than in the controls for all data sets. Relative humidity (RH) was on average 10% drier in the OTC where the average RH was 80. The relative humidity inside the chambers showed distinct diurnal patterns which consistently paralleled each small variation of the controls suggesting that there is good ventilation within the chamber. Temperature was found to not be uniform within the chamber, instead there are distinct vertical and horizontal patterns. In 1995 there were indications that the active layer was slightly deeper under the chambers than in the controls although at the beginning of the season and at the end of the season this was not the case. We believe that the hysteresis of the large permafrost mass surrounding these relatively small chambers dampens the progression of thawing and that the spatial variability of soil thaw makes small differences difficult to detect. The average temperature increase brought about by the chambers is realistic relative to the predicted magnitude of greenhouse warming. In several species the OTCs had a positive effect on the timing of leaf emergence, rate of flower development and maturation, and stature and senescence of leaves and stems. A few complacent species and a few significant reductions in growth were also observed. In combination with other LAII (Land-Atmosphere-Ice Interactions) studies and the results from the ITEX network, these continuing experiments will contribute to a better understanding of spatiotemporal variations in the arctic-climate plant system and making reasonable predictions on how arctic-plant community structure might change in the event of global warming. This work was supported by a grant to The Ohio State University, Kenneth Jezek, Principal Investigator from the Arctic System Science Program of the National Science Foundation.

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Barrow Canyon: A Model for Shelf-Basin Water Mass Exchange

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Much of the thermohaline and biogeochemical structure of the Arctic Ocean bears the signature of waters modified on its adjacent shelf seas. However, it is not clear how these water masses are carried across the shelf break and distributed throughout the central basin. Understanding the present day structure of the Arctic Ocean and its response to climate change requires a quantitative and dynamic understanding of the exchange between the shelf and basin, as well as knowledge of the large-scale circulation. We argue that shelf-break canyons play a crucial role in a two-way exchange between the shelf and the basin. Biogeochemical products from the shelf will be concentrated in dense shelf waters produced by sea-ice formation in winter. Canyons then funnel these dense waters across the continental slope and into the circumpolar, eastward-flowing boundary current. Far downstream from these source regions, upwelling in canyons can subsequently transfer these waters and their chemical constituents back onto the continental shelves. We view Barrow Canyon as a model for such exchanges, linking the Chukchi Sea shelf adjacent to Alaska with the large-scale basin circulation. We explore the likelihood and consequences of this scenario using current data from Barrow Canyon and the adjacent shelf and slope during the past ten years. While down-canyon flow prevails throughout most of the year, flow reversals are frequent in fall and winter. The reversals provide an on-shelf flux of heat and salt by advecting warm, salty slope water (from ~300 m depth) up the canyon to its head (~250 km distant), where bottom depths are only ~70 m. While the down-canyon flow usually advects relatively fresh water into the near-surface layers of the Arctic Ocean, in some winters, cold, hypersaline plumes formed on the Chukchi shelf move down the canyon. These plumes take the form of gravity currents affected by rotation, and they do not appear to mix with ambient shelf water as they descend. Hence, the plumes can easily ventilate the halocline and even deeper layers of the Arctic Ocean. The interannual variability in these various processes leads to strikingly different year-to-year manifestations of winter shelf-water properties and fluxes both onto and off the shelf. The transport of biogeochemical products on and off the shelf likely varies similarly.

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Observations and Modeling of the Chukchi Sea Shelf

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Current measurements in Bering Strait and the northeast shelf made from fall 1991-fall 1992 show steady, northward, mean monthly flow in all months except from November through January. At this time the shelf circulation was weak or southward over the northeast shelf while generally northward in Bering Strait. The observations imply convergent alongshore flow on the eastern half of the shelf and diversion of the strait inflow to the western Chukchi Sea. Much of the observed current variability is coherent with the regional wind. We examined the evolution of the shelf circulation using a 2-dimensional barotropic model forced by the winds and the secular sea-level difference between the Pacific and Arctic oceans. The latter establishes a sea-level slope between Alaska and Siberia whose magnitude diminishes proceeding northward from Bering Strait as the coastlines diverge. This effect, in conjunction with alongshore divergence in the alongshore wind velocity establishes the sea-level variations which account for the observed winter circulation. The fall-winter circulation was potentially significant in forming the dense water within the coastal polynyas of the northeast Chukchi Sea because the circulation:

1. diverted the low-salinity Bering Strait inflow away from the polynyas, and
2. prolonged the residence time of shelf water parcels within these polynyas.

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Biological Processes in the Central Arctic Ocean: Potential Effects of Climate Change

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Results from the 1994 Arctic Ocean Section show that there is significant primary production and heterotrophic activity under the permanent ice cover of the central arctic basins. We show nutrient distributions, standing stocks of lower trophic levels, primary production, and bacterial production. Estimates of primary production are tenfold greater than previous estimates, with most of the difference due to activity of the ice algae. Standing stocks are dominated by heterotrophic organisms, with microheterotrophs (bacteria and protists) accounting for 31% and mesozooplankton accounting for 50% of living carbon biomass. At times heterotrophic carbon consumption exceeded primary production. These results show that there is significant in situ production and cycling of carbon in the central Arctic Ocean. Our results indicate that primary production and other biological processes within the arctic basins need to be considered in evaluating the arctic carbon budget. Better estimates of annual production in the central Arctic require a seasonal study of production by ice algae and phytoplankton and of heterotrophic processes. The 1994 summer snapshot clearly indicates the presence of active carbon cycling, but the fate of production will be uncertain until we determine the coupling between autotrophic and heterotrophic processes over the seasonal cycle for the sea-ice communities and the water column. Global warming will have a significant impact on the ice cover of the Arctic Ocean. Results from the 1994 Arctic Ocean Section lead to the following predictions of effects of warming on primary production in the central Arctic. First, diminishing of ice cover will reduce substrate available for, and primary production by, ice algae. Second, reduced ice cover will increase light availability to phytoplankton and increase planktonic (water column) production. The control of primary production and thus carbon flow through the food web during the summer growing season could then be set by nutrient availability and its regulation by stratification of the water column. We hypothesize that significant reduction in ice cover will result in increased total primary production for the central Arctic. The effects of climate change on export of carbon will depend upon differences in the efficiency of carbon transfer through the food webs of the sea-ice and water-column communities.

For further information about this work, see:

Rich, J., M. Gosselin, E. Sherr, B. Sherr, and D.L. Kirchman. 1997. High bacterial production, uptake and concentrations of dissolved organic matter in the Central Arctic Ocean. *Deep-Sea Research II* 44 (8): 1645–1663.

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Temporal Changes in Availability of Caribou in Sensitive Habitats: Implications for Human Harvest

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A 12- to 15-year analysis shows inter-year variation in distribution of caribou which affects both herd recruitment and the availability of caribou for subsistence hunting. Inter-year variation in recruitment is related to seasonal ecological controls by abiotic and biotic surrogates of forage quality and availability, snow depth and melt off, and harassment by insects. We prioritized 16 seasonal habitats of the Porcupine Caribou Herd for their relative contribution to variability in herd recruitment and subsistence yield. Sensitive habitats were those ranked highest in priority.

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The Sublimation of Polar Ice Core Samples as a New Way of Obtaining Paleoclimatic Information

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In recent years, ice in polar ice sheets has become an increasingly important source of paleoenvironmental information. Polar ice cores provide perhaps the best way of obtaining samples for study of the earth's atmosphere at times in the past. This paper describes a novel technique for recovering information recorded in ice.

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Sr, Nd, and Pb Isotope Variations of Central Arctic Seawater and Silicate Sediment Throughout the Late Cenozoic: Implications for Sediment Provenance and the Source of Trace Metals in Seawater

Bryce L. Winter[1] (University of Wisconsin-Madison), Clark M. Johnson,[2] and David L. Clark[3]

Late Cenozoic sediments on the Alpha Ridge, central Arctic Ocean (~5 m thick) were deposited at very low sedimentation rates (~1 mm/k.y.) and can be separated into two distinct sedimentary packages based on lithology. The lower package (~5–2.4 Ma) is composed of silty lutites that are interpreted to have been deposited by sea ice. The upper sedimentary package (~2.4–0 Ma) is composed of alternating sandy and silty lutites, and has glacial drop stones occurring throughout the sequence. The younger cyclic sequence is interpreted to have been deposited by glacial ice; the coarse layers were deposited during glacial maximums and deglaciation, whereas the fine intervals were deposited during interglacial periods. The isotope (Sr, Nd, Pb) compositions of the siliciclastic fraction are homogeneous during the time period of sea-ice sedimentation (~5–2.4 Ma), whereas $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios progressively increase and $^{143}Nd/^{144}Nd$ ratios decrease during the time period of glacial sedimentation. We interpret these isotope variations to indicate a progressive change in the source of sediments to the central Arctic Ocean beginning at the time of initiation of continental glaciation (~2.4 Ma). All the isotope systems are remarkably consistent and indicate that the sediment source region during glacial sedimentation (~2.4–0 Ma) had a greater supracrustal component and/or an older average age relative to the source that supplied sediment during the time period of sea-ice sedimentation (~5–2.4 Ma). The success of isotope geochemical studies in determining the location of the source for lower latitude marine sediments has relied strongly upon the previous or concurrent acquisition of a data base for potential source regions (*e.g.*, rivers, coastal sediments, deltas, etc.). No such data exists for the Arctic Ocean. The approximate age and general chemical characteristics of the circumarctic continental masses are known, however, from crustal studies that have been carried out over the past ~20 years. These data and the contrast in the source areas of modern sea ice (Siberian Shelf) and ice bergs (Canadian Islands) in the Arctic Ocean allow us to construct a working hypothesis concerning the locations of the sources of Late Cenozoic sediment. The isotope data are consistent with derivation of the older (~5–2.4 Ma) sediment entirely from the Siberian Shelf, whereas the Canadian Island region became a progressively more important source of sediment since ~2.4 Ma. The general increase in the amount of coarse sediment since ~2.4 Ma is consistent with this hypothesis. We intend to further refine the location of the sources of sediment to the central Arctic Ocean, and understand sediment distribution patterns on the shelves by characterizing the geochemistry of circumarctic shelf and river sediments, as well as glacial tills which have been broadly correlated with the marine glacial deposits. Sr, as well as Nd and Pb isotope variations of arctic seawater during the Late Cenozoic, were determined by chemically concentrating the oxide fraction of Fe-Mn micronodules (50–300 μ) separates. Our calculations show that >97% of the Sr in the

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oxide fraction is derived from seawater, but minute contributions of very radiogenic Sr from silicate material during diagenesis or the chemical leaching procedure results in this technique not being useful for refining chronostratigraphy. Variations in the Pb and Nd isotope compositions of arctic seawater (*i.e.*, the oxide fraction) during the Late Cenozoic follow those of the siliciclastic fraction. This result reflects the short seawater residence time of Nd and Pb, and indicates that the continental sources that are supplying siliciclastic sediments are also controlling the isotope composition of arctic seawater, which is not the case in the central Pacific Ocean (Jones *et al.*, 1994).

For further information about this work, see:

Winter, B.L., D.L. Clark, and C.M. Johnson. 1997. Late Cenozoic Sr isotope evolution of the Arctic Ocean: constraints on water mass exchange with the lower latitude oceans. *Deep-Sea Research II* 44 (8): 1531–1542.

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Frozen Ground Dominates Arctic Hydrologic Response

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The hydrologic behavior of arctic watersheds is unique when compared to more temperate watersheds because of the presence of frozen ground, specifically permafrost and the frozen active layer. Field studies and modeling results both attest to the importance of frozen soils in the demeanor of arctic watersheds. The snowmelt, runoff response is enhanced because frozen ground limits infiltration and subsurface storage; evapotranspiration dominates during the summer months as the main mechanism of export from the watershed because of the shallow nature of the active layer. Seasonal patterns in radiative fluxes also add a distinct flavor to the behavior of arctic watersheds. After a few days of above freezing temperatures, the thin veneer of snow becomes isothermal. Runoff peaks are reached precipitously and a high percentage of the snowpack can be expected to leave the watershed as runoff, with the remainder going into surface and soil storage or leaving the watershed as evaporation. Subsurface storage increases during the summer months as thawing occurs. Also the ratio of old water to new water increases in the runoff during the summer months as the active layer thaws. Reasonable results from a physically based, spatially distributed hydrologic model have been obtained for a small arctic watershed.

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Seasonal and Interannual Sea-Ice Variability in a High Resolution Coupled, Arctic-Ice Ocean Model

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Results from a high-resolution (18 km), coupled, arctic-ice ocean model are presented. The ice model is based on the Hibler (1979) dynamic/thermodynamic sea-ice model with more efficient numerics (Zhang and Hibler, 1997). The ocean model is based on the Semtner and Chervin (1992) free-surface ocean model. The model covers the Arctic Basin and adjacent seas, including the Nordic and Labrador seas, and the Baffin and Hudson bays. Three-day averaged 1990–94 ECMWF winds and heat fluxes are used to drive the coupled model. With high-resolution and high-frequency forcing, the model is able to simulate in great detail the complex structure and movement of sea ice. Video animation (every 3 days for each frame with a total of 606 frames for 5 years) illustrates opening and closing of Northeast Water polynyas (off the extreme northeastern Greenland) and smaller coastal polynyas farther south along the eastern Greenland coast. In addition, North Water polynyas (in Baffin Bay and Smith Sound), polynyas in the vicinities of Novaya Zemlya, Severnaya Zemlya, and Franz Josef Land, and in the Canadian Archipelago are also well simulated. The ice vortex at the edge of the East Greenland Current has a striking resemblance to one in the observational study by Wadhams and Squire (1983). The Odden (eastward extension of sea ice in the Greenland Sea near Jan Mayen Island) and Nordbukta (embayment of sea ice to the north of Odden) phenomena studied by Carsey and Roach (1994) using satellite and in situ data are reproduced by the model. Low ice concentration within the arctic pack ice of Canada Basin reported by Barry and Maslanik (1989) using SMMR data and drifting buoys is also presented in the ice compactness from the model output. Arch-shaped cracking of ice appear in many places over the Arctic Basin. In summary, the model is able to simulate the variation of arctic sea ice with detail never before achieved. To quantify the spatial distribution of the ice extent and its seasonal and interannual variability, time series of the ice extent, ice area, and open water within ice pack over various regions are calculated. Comparison with SMMR observation (Gloersen *et al.*, 1992) indicates that this model realistically simulates the seasonal trends in regional ice growth and decay. The mass transport of ice through Fram Strait is in reasonable agreement with Vinje and Finnekasa's (1986) estimation. The monthly mean of ice compactness from the model output very much resembles the ice concentration from the DMSP-F8/F-11 SSM/I data.

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Development of a Holocene Multivariate Paleoclimatic Record from the Penny Ice Cap, Baffin Island, Arctic Canada

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In April 1995, a 334 m-long surface-to-bottom ice core was recovered from the summit of the Penny Ice Cap (67°15'12" N; 65°46'12" W) on southeastern Baffin Island. The project was undertaken as a joint research effort between the Glacier Research Group (GRG) at the University of New Hampshire and the Geological Survey of Canada (GSC). The ice core was sampled at high resolution and is currently being studied for physical stratigraphy, conductivity, $\partial^{18}O$, major ion chemistry, microparticles, and pollen content. A preliminary analysis indicates that the ice-core record spans the entire Holocene epoch and extends beyond the Last Glacial Maximum. The multivariate physical and glaciochemical time series compiled from the Penny ice core will be used to document climatic variability and atmospheric composition in the eastern arctic region over the last 10,000 years or more. The proximity of the Penny Ice Cap to the North Atlantic region, the North American mainland, and to a major climate boundary (the polar front), makes it a potentially sensitive site to environmental changes occurring in this sector of the Arctic. The record from Penny Ice Cap will also complement those of nearby coring sites from Greenland (Dye3, GISP2, GRIP cores) and the Canadian Arctic (Devon and Agassiz cores). A preliminary age-depth scale has been constructed for the Penny ice core based on ice-flow modeling tuned to characteristic features of the $\partial^{18}O$ time series and to known volcanic markers identified from ECM and sulfate measurements. High-resolution time series of major chemical species (Ca, Cl, Mg, Na, K, NH_4, NO_3, and SO_4) have been compiled for the last ~3,000 years of record (294 m depth), and work is ongoing to extend the time series over the remaining 40 m of the core. It is expected that decadal-scale resolution can be attained over the entire Holocene record. Annual chemical signals in the core are identifiable to a depth of at least 70 m, which has allowed for accurate layer counting down to A.D. 1783. A record of melt features in the core is also being compiled, which will provide a proxy for relative summer warmth over the last few centuries. Other objectives include a comparative study of the composition of airborne dust microparticles deposited in snow at different time periods on the Penny Ice Cap and at other arctic sites (GISP2, Devon Island, Agassiz Ice Cap). Data from this aspect of the study may be used to highlight changes in atmospheric circulation patterns in the Arctic over the last 10–15 ka. Paleoclimatic information from the Penny Ice Cap record will complement other sources of proxy data such as tree-ring records and lake-sediment cores currently being retrieved from various eastern arctic sites. The Penny Ice Cap project is the first of a series of concerted efforts in the newly developed IGBP Ice-core CircumArctic Paleoclimatic Programme (ICAPP).

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Workshop Agenda

Arctic System Science (ARCSS) Program
All-Hands Workshop
30 April - 3 May 1996
Snowbird, Utah

TENTATIVE PROGRAM
W. Berry Lyons, Chair

Tuesday, 30 April 1996

9:00 a.m. - 5:00 p.m.	LAII Science Steering Committee Meeting	Board Room
4:00 p.m. - 9:30 p.m.	All-Hands Workshop Registration	Ballroom Lobby
6:00 p.m.	The Role of the Active Layer and Permafrost in Land-Atmosphere Interactions	White Pine
6:00 p.m. - 7:00 p.m.	Planning: Synthesis and Working Group Chairs	Magpie A
7:00 p.m. - 9:30 p.m.	Icebreaker Reception and Poster Session	Ballroom II

Wednesday, 1 May 1996

7:00 a.m.	Registration	Ballroom Lobby
PLENARY	Ballroom I	
8:00 a.m.	Welcome, Introductions, and Comments	*W. Berry Lyons*
8:15 a.m.	Why Are We Here?	*Mike Ledbetter, NSF-ARCSS Program Director*
8:45 a.m.	The color of global change: variability in the polar regions	*Warwick Vincent, Centre for Northern Studies, Laval University, Quebec City, Canada*

9:15 a.m. The Arctic System Science (ARCSS) Program Overview
(20 minutes, including Q&A)

- Large, abrupt, global climate changes of the past—and the future? The GISP2 Record .... *Richard Alley*
- Spatial variability in environmental change across the Arctic .... *Gifford Miller*
- An OAII Program Update: Research Findings and Priorities .... *Jackie Grebmeier*

10:15 a.m. BREAK

10:30 a.m. The Arctic System Science (ARCSS) Program Overview (cont.)

- Land-Atmosphere-Ice Interactions Overview .... *Terry Chapin*
- The dynamics of human/environmental linkages at community, regional, and global scales .... *Carl Hild*
- ARCSS Modeling and Synthesis, Integration, and Modeling Studies (SIMS) .... *Amanda Lynch*
- Data Coordination .... *David McGinnis*

12:00 p.m. Lunch (OAII SSC will meet in the Board Room)

1:00 p.m. ARCSS Program Research (30 minutes each component, including Q&A):

- The rapidly changing arctic environment: a paleoenvironmental perspective .... *Jonathan Overpeck*
- A long-range plan for research on land-atmosphere-ice interactions in the Arctic .... *Gunter Weller*
- A multidisciplinary look at the Arctic Ocean .... *Knut Aagaard*
- Overview of SHEBA: Surface Heat Budget of the Arctic Ocean .... *Richard Moritz*
- Models of environmental impact on humans .... *Andrew Kerr*

3:00 p.m. BREAK

3:15 p.m. Integrated, interdisciplinary approaches to understanding the arctic system (20 minutes, no Q&A)

- Environment, Resources, and People .... *Patrick Webber*
- Temporal and Spatial Dynamics .... *John Andrews*
- The Arctic System .... *John Walsh*

4:15 p.m. Panel/Plenary Discussion .... Facilitator: *Douglas Siegel-Causey*

WORKING GROUPS

4:45 p.m. Working Groups 1-10 .... Breakout Rooms TBA

1. Detection of temporal change: past, present, and future
   Co-chairs: *Gifford Miller, Thomas Weingartner*
2. Detection of spatial change: past, present, and future
   Co-chairs: *Pat Anderson, Skip Walker*

3. Scaling issues and problems
   Co-chairs: *John Hobbie, David Chapman*
4. Variability within the arctic system
   Co-chairs: *Knut Aagaard, Jonathan Overpeck*
5. Assessment of the impact of global change on the arctic system
   Co-chairs: *Richard Alley, Robert White*
6. Coastal interface and processes
   Co-chairs: *Steve Forman, James Sedinger*
7. Implications of resource variability for human societies
   Co-chairs: *Nicholas Flanders, Astrid Ogilvie*
8. Development and Sustainability of Arctic Resources
   Co-chairs: *Patrick Webber, Gail Fondahl*
9. The Arctic in 2050—the state of the environment and living resources
   Co-chairs: *Jack Kruse, Berry Lyons*
10. Moving toward an integrated arctic system model
   Co-chairs: *John Walsh, Richard Moritz*

5:30 p.m. Poster Session .... Ballroom II and Ballroom Lobby

6:30 p.m. Reception/Poster Session .... Atrium

7:30 p.m. Banquet .... Ballroom I

Banquet Special Guest Speaker:

Zimbabwe's CAMPFIRE: Integrating Rural Development and Community
Environmental Management in Africa .... *Leslie King*
Chair, Environmental Studies
University of Northern British Columbia

Thursday, 2 May 1996

7:00 a.m. ARCSS Advisory Committee .... Aerie Restaurant (10th floor)

7:30 a.m. Registration .... Ballroom Lobby

PLENARY Ballroom I

8:00 a.m. A new perspective on climate change from ice cores .... *Paul Mayewski*
Director, Climate Change Research Center
University of New Hampshire

WORKING GROUPS

8:30 a.m. Working Groups 1-10 ....Breakout Rooms TBA

1. Detection of temporal change: past, present, and future
   Co-chairs: *Gifford Miller, Thomas Weingartner*
2. Detection of spatial change: past, present, and future
   Co-chairs: *Pat Anderson, Skip Walker*

3. Scaling issues and problems
   Co-chairs: *John Hobbie, David Chapman*
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8. Development and Sustainability of Arctic Resources
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9. The Arctic in 2050—the state of the environment and living resources
   Co-chairs: *Jack Kruse, Berry Lyons*
10. Moving toward an integrated arctic system model
   Co-chairs: *John Walsh, Richard Moritz*

10:30 a.m. BREAK

10:45 a.m. First Synthesis Session: .... Breakout Rooms TBA
A. Temporal and Spatial Dynamics—*Chair, Julie Brigham-Grette*
Working Groups 1, 2, 3, and 4
B. Environment, Resources, and People—*Chair, David Klein*
Working Groups 6, 7, 8, and 9
C. The Arctic System—*Chair, Gunter Weller*
Working Groups 5 and 10

12:00 p.m. LUNCH (HARC SSC Meeting—lunch provided—Cliff Suite 517)

12:00 p.m. - 1:00 p.m. Lunch meeting for interested investigators: .... Cliff Suite 417
Impact of vegetation change on hydrologic budget of the arctic basin and North Atlantic deep water formation
(box lunch available for $9)

1:00 p.m. Working Groups 1-10 .... Breakout Rooms TBA
1. Detection of temporal change: past, present, and future
   Co-chairs: *Gifford Miller, Thomas Weingartner*
2. Detection of spatial change: past, present, and future
   Co-chairs: *Pat Anderson, Skip Walker*
3. Scaling issues and problems
   Co-chairs: *John Hobbie, David Chapman*
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8. Development and Sustainability of Arctic Resources
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9. The Arctic in 2050—the state of the environment and living resources
   Co-chairs: *Jack Kruse, Berry Lyons*
10. Moving toward an integrated arctic system model
   Co-chairs: *John Walsh, Richard Moritz*

3:00 p.m. BREAK

3:15 p.m. Second Synthesis Session: .... Breakout Rooms TBA
A. Temporal and Spatial Dynamics—*Chair, Julie Brigham-Grette*
Working Groups 1, 2, 3, and 4
B. Environment, Resources, and People—*Chair, David Klein*
Working Groups 6, 7, 8, and 9
C. The Arctic System—*Chair, Gunter Weller*
Working Groups 5 and 10

5:00 p.m. Poster Session .... Wasatch A & B

6:30 p.m. Adjourn

Thursday evening, 2 May 1996
Meetings for Interested Investigators

7:00 p.m. -
8:00 p.m. Ice-core meeting: future arctic coring operations .... Superior B

7:00 p.m. -
9:00 p.m. OAII General Meeting .... Ballroom I

7:00 p.m. -
9:00 p.m. PALE principal investigator meeting .... Magpie A

7:30 p.m. The role of snow and snow cover in the Arctic .... Superior A

Friday, 3 May 1996

7:30 a.m. Registration for Saturday, 4 May 1996 Logistics Workshop

PLENARY	Ballroom II
8:00 a.m.	The social and biophysical as coupled systems .... *Oran Young* *Director, Institute of Arctic Studies* *Dartmouth College*
8:30 a.m.	Reports from Synthesis Groups A. Temporal and Spatial Dynamics—*Chair, Julie Brigham-Grette* B. Environment, Resources, and People—*Chair, David Klein* C. The Arctic System—*Chair, Gunter Weller*
10:45 a.m.	BREAK
11:00 a.m.	Discussion of Synthesis Group Recommendations
12:00 p.m.	LUNCH (HARC SSC Meeting—lunch provided—Cliff Suite 517)
1:00 p.m.	Third synthesis session: .... Breakout Rooms TBA A. Temporal and Spatial Dynamics—*Chair, Julie Brigham-Grette* Working Groups 1, 2, 3, and 4 B. Environment, Resources, and People—*Chair, David Klein* Working Groups 6, 7, 8, and 9 C. The Arctic System—*Chair, Gunter Weller* Working Groups 5 and 10
2:00 p.m.	Reports from Synthesis Groups .... Ballroom II A. Temporal and Spatial Dynamics—*Chair, Julie Brigham-Grette* B. Environment, Resources, and People—*Chair, David Klein* C. The Arctic System—*Chair, Gunter Weller*
3:00 p.m.	BREAK
3:15 p.m.	Development of Recommendations .... Facilitator: *Douglas Siegel-Causey*
4:30 p.m.	Summary and Comments .... *W. Berry Lyons*
5:00 p.m.	Adjourn Workshop
7:00 p.m. - 9:30 p.m.	SHEBA Meeting .... Maybird

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