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Foreword

A complex suite of significant and interrelated atmospheric, oceanic, and terrestrial changes has occurred in the Arctic in recent decades. The Study of Environmental Arctic Change (SEARCH) is an interagency effort to understand the causes, connections, and consequences of these environmental changes, emphasizing interactions with global climate change and potential impacts on the arctic system including the physical, chemical, biological/ecological, and social domains.

To explore the SEARCH premise, researchers from around the world presented and discussed evidence of rapid environmental change in the Arctic at the first SEARCH Open Science Meeting (OSM). Over 440 social and natural scientists, policy makers, and stakeholders from 18 countries met in Seattle, Washington, on 27–30 October 2003. This abstract volume represents the diversity and interdisciplinary nature of arctic research and clearly indicates that the science behind SEARCH is firmly established.

SEARCH is now moving from a pilot phase to a fully implemented program. Building on the enthusiasm and commitment of the arctic research community following the OSM, SEARCH initiated discussion on establishing an international counterpart, which presently is being developed as the International Study of Arctic Change (ISAC) with sponsorship from the Arctic Ocean Sciences Board (AOSB) and the International Arctic Science Committee (IASC). SEARCH and ISAC will provide long-term science programs that will deliver the knowledge base required for scientific analysis as well as future impact assessments and mitigation strategies, and will provide platforms for accelerated implementation of integrated studies on the international level. Continual community involvement will be critical in prioritizing and implementing SEARCH science.

On behalf of the SEARCH Science Steering Committee and the OSM organizing committee, we would like to thank the meeting's sponsors, participants, session chairs, and organizers. The ARCUS staff, led by Wendy Warnick and Helen Wiggins, provided excellent organizational support at the meeting and in the preparation of this volume. Thanks are also due to David Marusek of Attention Graphics and Sarah Behr and Alison York of ARCUS for their work in the design and completion of these proceedings. The meeting and these proceedings are possible through sponsorship from the National Science Foundation Office of Polar Programs, with additional support from the SEARCH Interagency Program Management Committee and the International Arctic Science Committee.

Peter Schlosser, Chair SEARCH Science Steering Committee
James Overland, Chair OSM Organizing Committee

Across the Arctic, scientists and local communities have recorded alarming environmental changes in the land, sea and air, including warmer temperatures, thinning sea ice, and thawing permafrost. In recent years, scientists investigating the arctic environment have collected significant data because of improved access to the central Arctic Ocean, new technologies, better agency and international cooperation, and partnerships with local communities. These data point to a widespread and interrelated suite of changes across the physical, biological, and social realms of the Arctic. These changes are likely to have global significance—climatic processes unique to the Arctic have major effects on global and regional climate. The Arctic also provides natural resources to the global economy that will be affected by change.

The Study of Environmental Arctic Change (SEARCH) is an interdisciplinary and interagency effort to understand the causes, connections, and consequences of the observed recent arctic environmental changes, emphasizing their interactions with global climate change and potential impacts on the biosphere, including human social and economic well-being.

The SEARCH Science Plan, published in 2001, articulates the scientific rationale, hypotheses, objectives, and strategy of SEARCH. Currently, more than 40 projects are funded as SEARCH activities by U.S. agencies, and many more projects relevant to SEARCH objectives are supported through other programs.

With the increasing evidence of widespread changes, and the increasing number of projects in a myriad of disciplines related to arctic environmental change, the SEARCH Open Science Meeting was convened to:

- share evidence of environmental change in the Arctic,
- identify results from individual research projects that could inform the overall SEARCH objectives, and
- contribute to the SEARCH program either through linking their ongoing work to this program or through the design of new projects.

Community Response

The community interest in SEARCH science was evident by the response and enthusiasm at the meeting; over 440 social, physical and natural scientists, students, policy makers, and stakeholders attended the meeting. Of note was the large international interest; approximately one-fifth of the participants at the OSM came from countries outside the U.S. In all, 18 countries, including all of the eight arctic nations, were represented.

All of the OSM sessions were enriched by the valuable participation of undergraduate and graduate students. A student scholarship program, sponsored by the National Science Foundation Office of Polar Programs (NSF-OPP), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy Atmospheric Radiation Measurement Program (DOE-ARM), the Alaska Native Science Commission (ANSC), and the Arctic Research Consortium of the U.S. (ARCUS), provided full or partial funding of conference expenses for 45 students, and a student poster competition awarded winners sponsorship to attend a future scientific conference. The contributions of these young investigators were critical to the success of the SEARCH OSM.

Several members of the news media, including reporters from the *New York Times*, the *Seattle Times*, the *Seattle Post-Intelligencer*, and Alaska Public Radio, attended the OSM. A press conference was held simultaneously in Seattle and Washington, D.C. and streamed online. Media coverage of the conference resulted in a significant number of print, radio, television, and Internet stories, which are available through the ARCUS website: www.arcus.org/SEARCH/meetings/2003/mediacoverage.php.

Science Themes
The SEARCH OSM was organized around the broad themes of changes and impacts, feedbacks, and drivers and causes. The OSM included over 280 oral and poster presentations reporting on a variety of investigations, including direct observations, proxy records, modeling studies, and community projects.

Changes and Impacts
Presentations provided evidence of widespread and potentially interrelated changes in the land, sea, atmosphere, and coastal systems, including lower sea-level atmospheric pressure, increased surface air temperatures, increased soil temperatures, thawing permafrost, negative glacier mass balance, growth responses in vegetation, shifts in species composition of arctic and subarctic ecosystems, decrease in sea ice, and changing biogeochemical cycles. Several presentations pointed to an increased rate of change in recent years. Presentations from arctic residents and human dimensions researchers underscored the immediate impacts environmental changes are having on human communities in the context of other political, economic, social, and environmental forces of change. Several approaches to working with communities and incorporating residents' contributions were presented as models to integrate social science and local knowledge into arctic change research.

Feedbacks
Social, biological, and physical feedbacks, both within the Arctic and to the global system, are critical components in the development of a fundamental understanding of current changes and predictions of future change. Presentations and discussions helped to elucidate the definition and nature of feedbacks, evidence for feedbacks between components and systems within the Arctic that could accelerate or mitigate warming, and feedbacks between the Arctic and lower latitudes. Emerging evidence suggests that the suite of identified feedbacks have the potential to lead to abrupt climate change.

Drivers and Causes
Two of the working hypotheses of SEARCH (see SEARCH Science Plan) address drivers and causes of arctic change, namely, the relation of recent changes to both natural atmospheric circulation patterns (e.g., the Arctic Oscillation) and anthropogenic climate change. Presentations at the OSM reported on a variety of topics to provide insight into relative contributions of both natural and anthropogenic drivers. Presentations emphasized patterns of spatial and temporal variability of climatic variables and processes, and placing present change in context of historical and paleo records.

Conclusions and Next Steps

The SEARCH Open Science Meeting provided a venue for sharing recent scientific findings on a broad scope of issues related to environmental arctic change. The enthusiasm of the community and legacy of research have created a foundation on which to build, in order to detect, understand, and respond to arctic environmental change. The SEARCH Science Steering Committee (SSC), the SEARCH Interagency Program Management Committee (IPMC), and the broader community is working to improve coordination among disciplines, research initiatives, and international borders.

Through further investigation of the broad themes outlined in the SEARCH Science Plan and reflected in the presentations at the OSM, the SEARCH science community can advance observations, modeling, process studies, and application of knowledge towards understanding changes and impacts with the ultimate goal of predicting and adapting to arctic climate change.

Introduction

Development of the SEARCH program began in the mid-1990s, as a number of scientists became concerned about the magnitude of the changes they were observing in arctic ocean and atmospheric conditions. Led by James Morison at the University of Washington, the group circulated an open letter to the scientific community proposing a program to track and understand major changes in the arctic environment. By 1997, 40 scientists from 25 institutions had signed the letter, calling for an international effort to investigate those changes through measurement, data analysis, and modeling. The letter was endorsed by the NSF Arctic System Science (ARCSS) Ocean–Atmosphere–Ice Interactions Science Steering Committee.

With support from the ARCSS Program, the University of Washington hosted an open workshop in 1997 on the Study of Arctic Change. More than 70 scientists reported on recent ocean and atmospheric changes in the Arctic, corroborating earlier observations and suggesting a related suite of changes that were arctic-wide. As the effort developed, its name changed to the Study of Environmental Arctic Change (SEARCH), and SEARCH advanced beyond sponsorship by the ARCSS Program to a broader initiative involving several federal agencies.

In 1999, the Interagency Arctic Research Policy Committee (IARPC) included SEARCH as "ready for immediate attention" in the U.S. Arctic Research Plan, and a SEARCH Interagency Working Group (IWG; now Interagency Program Management Committee, IPMC) chaired by NOAA was established and tasked. The IPMC consists of the eight federal agencies responsible for scientific research in the Arctic that have agreed to work together on SEARCH. A SEARCH Science Management Office and chair were established at the University of Washington's Applied Physics Laboratory, and the SEARCH Science Plan was published in 2001. The SEARCH Implementation Strategy, outlining science questions, program organization, and implementation activities and priorities, was published by the SEARCH SSC and IPMC in 2003 and widely circulated at the Open Science Meeting. For more information, see the SEARCH Science Management Office website: www.arcus.org/SEARCH.

Co-chairs: **Matthew Sturm** Cold Regions Research and Engineering Laboratory, **Bruce Forbes** University of Lapland

The abstracts from the talks and posters presented during the Changes on Land session can be found on pages 19–72. This session detailed a variety of changes to land surface systems as determined through direct observation or model simulations. It also provided some insight into land surface change that might occur under a variety of climate change scenarios in the future.

In general, past changes on land are broadly consistent with the patterns of change predicted by climate and ecosystem models. Changes to permafrost, vegetation, glaciers, and other hydrological systems provide evidence for a warming climate during the past 50 to 100 years. The rate at which change has occurred during the past 10 to 20 years seems to be increasing. At the same time, the amount of anthropogenic surface disturbance in the past 30–50 years has been significant in certain regions, such as northwest Russia. Both direct and cumulative anthropogenic changes interact in important ways with climate-driven changes and need to be accounted for in modeling efforts. There is uncertainty regarding future change, but studies suggest a continued reduction in permafrost extent, a decrease in vegetation species diversity, a northward movement of trees and shrubs, an increase in the contribution of glaciers and ice sheets to sea level rise, and an alteration of thermohaline circulation due to changes in fresh water run-off.

This session covered changes in four land surface systems:

- permafrost,
- vegetation,
- hydrology, and
- glaciers.

Permafrost

From the talks and posters concentrated on permafrost structure and extent, the following observed changes/feedbacks were identified:

- Between 1989 and 2002, near-surface mean annual permafrost temperatures have increased an average of 3° C.
- Active layer depths have increased approximately 11 cm during the period 1956–90 in Russia. The freezing layer depth has increased by 33 cm during the same time period.
- Extensive degradation of the surfaces of ice wedges in northern Alaska has occurred over a 57-year period, with the rates of degradation increasing during the past several decades.
- Modeling suggests arctic soil temperatures have increased during the past 20 years, with greatest increases occurring during the period 1994–2001.
- Siberian rivers are receiving less continental runoff during the summer and increased continental runoff during the winter due to decreases in permafrost extent.

The following changes/feedbacks are anticipated in the future:

- The permafrost active layer will become thicker, the lower boundary of permafrost will become shallower, and permafrost extent will decrease in area.
- Permafrost changes will alter surface water and energy balances. A thicker active layer will increase soil moisture storage capacity and runoff lag time will increase. Over longer periods, soils are likely to dry.
- Thinner permafrost will increase connections between surface and subsurface water.
- Reduced permafrost extent will result in greater infiltration of surface water to ground water, potentially changing the seasonal distribution of continental runoff and seawater chemistry.
- A thicker active layer will increase sediment loads delivered to the ocean and cause surface soils to become drier. Drier soils feedback to local and regional climate by altering the surface energy balance (sensible and latent heat fluxes).
- Ice wedge degradation will continue even in areas of cold continuous permafrost.
- Human-induced permafrost degradation in parts of northern Russia (e.g. Nenets and Yamal-Nenets Autonomous Regions) is likely to be increasingly significant due to intensive oil and gas development and extensive pressure from large and growing herds of reindeer.

Vegetation

From the talks and posters concentrated on vegetation, the following observed changes/feedbacks were identified:

- Interior Alaska low elevation upland white spruce show negative radial growth with increasing summer temperatures.
- Interior Alaska black spruce and birch show complex radial growth responses to increasing temperatures that are specific to populations, aspects, and/or topographic positions.
- In northwest Russia, changes in vegetation structure and cover associated with post-WWII patterns of industrial development and massive semi-domestic reindeer herds are significant and likely to continue as oil and gas activities expand and animal populations remain at current levels or increase.

The following changes/feedbacks are anticipated in the future:

- Global Climate Model (GCM) scenarios suggest that some populations of interior Alaska tree species may not survive over the next 70–100 years. This will result in an overall reduction in species diversity.
- Changes in vegetation cover will alter the surface energy balance and affect snow cover distribution.

Hydrology

From the talks and posters concentrated on hydrology, the following observed changes/feedbacks were identified:

- A trend towards earlier breakup of the Mackenzie River at Inuvik and earlier spring snowmelt in northwest Canada.
- An increase in annual discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean.

The following change/feedback is anticipated in the future:

- Increases in fresh water discharge may alter ocean thermohaline circulation.

Glaciers

From the talks and posters concentrated on glaciers, the following observed changes/feedbacks were identified:

- A sample of 72 glaciers in Alaska, Yukon, and northwest British Columbia showed an average thickness change rate of -0.5 m a^{-1} during the 1950s to mid-1990s. Repeat measurements on 48 of these glaciers show the rate of thinning has almost doubled during the mid-1990s to 2000–01.
- Detailed studies on three benchmark glaciers show correlations between annual mass balances and interdecadal climate-regime shifts during 1967–77 and 1989. All three glaciers showed strong negative trends during the 1990s.
- Reduction in glacier extent exposes low albedo rock surfaces, increasing surface radiation absorption and enhancing climate warming.
- Not all glacier changes are signals of climate change: some types of glaciers, such as tidewater and surging glaciers, have dynamic cycles not directly controlled by climate.

The following change/feedback is anticipated in the future:

- Glacier response to future changes in climate depends on glacier geometry and the nature and seasonal distribution of climate changes. Glaciers will lose mass if summer temperatures increase and snowfall amounts decrease. The effects of an increase in total precipitation on glacier mass balance will depend on the warming accompanying the precipitation changes. If precipitation increases together with air temperature, then more precipitation may fall as rain instead of snow, causing a decrease in glacier mass.

Implications of Observed and Future Changes

Changes on land affect arctic systems and arctic societies. For example, increases in permafrost active layer depth and reduction in permafrost extent may cause a higher frequency of engineering and construction problems in arctic regions, especially in northern Russia where oil and gas development over large areas is proceeding quickly and with minimal oversight with regard to environmental mitigation. Changes in arctic vegetation distribution due to both climate and more direct anthropogenic drivers may alter wildlife distribution and affect subsistence hunting patterns.

The complex suite of arctic changes also affects other global systems. Sea level rise associated with glacier volume loss may affect global communities living at coastal regions near sea level. Sea level changes affect the rate of saltwater incursion into coastal estuaries; a change in sea level may disrupt the balance of these ecosystems. Changes on land may feedback to atmospheric changes and alter global weather patterns. An example would be a change in arctic land surface albedo, which would change the surface energy balance.

Conclusions

Many observed changes on land provide evidence for an overall increase in temperature in arctic regions, with the rate of change increasing during recent years. These changes are interrelated and there are numerous feedbacks between individual components of the system. Interdisciplinary studies are required to understand the complexities of these changes, including interactions between climate and more direct anthropogenic influences. Human populations with close ties to the land and sea are likely to have relevant observations from the past 30–50 years.

Session Summary: Changes in the Sea

Co-chairs: **George L. Hunt** University of California Irvine, **Motoyoshi Ikeda** Hokkaido University

The abstracts from the talks and posters presented during the Changes in the Sea session can be found on pages 73–132. This session focused on evidence for changes in key components of the ocean system at multiple temporal and spatial scales including:

- atmosphere-ice-ocean systems, and
- ecosystem linkages.

Most scientists now concur that unusual changes are occurring in both arctic and sub-arctic marine systems; it is hard to make this case convincingly, however, without longer time series. In contrast to our ability to model the sub-arctic and arctic atmosphere-ice-ocean boundary layer, in the Arctic Ocean interior there is insufficient information concerning geochemistry and ecosystem properties to evaluate the extent and causes of change. Our knowledge of the decadal-scale variability of geochemical and ecosystem components of the arctic marine system should be reconstructed via modeling or improved by obtaining new data. The acquisition of data will then lead to both better understanding and more accurate parameterization of processes being modeled. Thus, research on the arctic geochemical ice-ocean system and ecosystem is required. Success in these challenges is a key to reliable prediction of environmental arctic change.

Atmosphere-Ice-Ocean Systems

Participants found that there has been considerable change in both arctic and sub-arctic marine systems over recent decades. In the Arctic Ocean, temperatures are rising, the water is saltier, there is less ice, and sea levels are rising. In the sub-arctic seas, there is also a rise in seawater temperatures, as well as earlier retreat of ice, an earlier transition to spring and, in some areas, a trend toward freshening of the waters.

In the Arctic Ocean and sub-arctic seas, in addition to long-term trends, there are significant decadal and multi-decadal variations in the atmosphere-ice-ocean boundary layer. The mechanisms of these trends and variations are amenable to modeling studies, and we are relatively confident about the effects of the atmosphere on the physical ice-ocean system. It is noted that the analysis of feedbacks from the ice-ocean system to the atmosphere has not been completed.

Ecosystem Linkages

In the sub-arctic seas there is also strong evidence for biological variability in response to variable physical forcing, and it seems feasible to begin modeling these interactions. The primary production models of the mid- and low-latitude oceans may provide a useful starting point for examination of higher latitude ecosystems. Ice algae is a special feature of high latitude oceans, and its role must be clarified and included in the arctic models. We are only beginning to understand the potential for organisms to provide feedback into physical processes in the Arctic Ocean.

The session did not discuss in-depth the implications of these changes and feedbacks for the long term sustainability of arctic ecosystems and the lifeways of people dependant on them. From this session it was clear that, with warming of some regions and the deterioration of ice thickness and duration, there would be major changes in the availability of prey organisms such as ice seals to hunters. In other cases, fish species previously excluded from the higher latitudes by cold water temperatures might now invade the arctic waters, providing new sources of food for people and new competitors for benthic resources vital to marine mammals presently abundant in the region.

Conclusions

Although there are clearly changes in these marine systems that were not observed in the past, it is hard to separate natural decadal-scale (Arctic Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation) variability from anthropogenically-induced variability. There is an overwhelming need for more data collection and analysis of arctic and sub-arctic marine systems. From a global perspective, changes occurring in the Arctic are bellwethers for future global change. It remains critical to document and understand these changes and their implications.

Co-chairs: **Hans von Storch** GKSS Research Centre, **Richard E. Moritz** University of Washington

The abstracts from the talks and posters presented during the Changes in the Atmosphere session can be found on pages 133–151.

Two major topics, observations of atmospheric change and atmospheric modeling, were discussed in this parallel session.

Observations of Change
Major findings from the talks and posters focused on this topic included:

- An Empirical Orthogonal Functions (EOF) analysis of multivariate environmental time series showed significant low frequency coherence among more than half of the 86 variables over the 20th century. The results also highlighted the sparseness of available observations prior to about 1960.
- Several papers presented estimates of arctic temperature, wind, cloud, and radiation derived from the 22-year time series of radiance measurements by the satellite-borne TIROS Operational Vertical Sounder (TOVS). The analyses revealed intriguing trends and interdecadal differences in clouds, temperature, and radiation.
- An overview of research on the budgets of particulate and gaseous contaminants in the Arctic emphasized the role of the atmosphere (e.g., the annual cycle of arctic haze) and stressed the needs and opportunities for collaborative research among chemists, atmospheric scientists, and the global change community.
- Huybers et al. used multivariate paleoclimate indicators to estimate EOFs of arctic surface temperature for the past 500 years. EOF #3 resembles the Arctic Oscillation (AO) and exhibits several intervals of large (comparable to 1960–2000) interdecadal variations in amplitude prior to the 20^{th} century.

Atmospheric Modeling
Observations from the talks and posters on atmospheric modeling included:

- Von Storch, Bromwich, and Hines addressed the problem of estimating consistent, mesoscale fields of atmospheric variables using different approaches. Von Storch assimilates only large-scale (e.g., NOAA National Centers for Environmental Prediction [NCEP]) input, and over Europe his method produces useful mesoscale fields of Sea Level Pressure (SLP). Bromwich proposes an arctic reanalysis that would assimilate all local data and that would ultimately extend to non-atmospheric variables.
- Sorteberg et al. presented results from simulations with the Bergen Climate Model forced by gradually increasing Greenhouse Gases (GHG). An ensemble of simulations was initialized by selecting initial conditions from the control run corresponding to different phases of the interdecadal variation in the Atlantic Meridional Overturning Circulation (AMOC) exhibited by this model. Most of the simulations showed an increasing trend in the North Atlantic Oscillation (NAO)

index and increased precipitation in the Arctic.

Open discussions followed each half of the oral presentation session. The following topics were discussed:

1. What are measures of the robustness of observed low frequency changes? One measure is physical consistency of changes in related variables, such as temperature, radiation, cloudiness, and sea level pressure. Another measure is statistical significance in light of contributions of random (e.g., weather) variability to the low frequency sample statistics. A difficulty is to estimate the low frequency variance of natural variability alone.

2. What distinctions should be made concerning the character of temporal change, i.e., "trend" vs. "regime shift" vs. "oscillation"? At least in part, this depends on the hypothesized causes and mechanisms that might explain the changes.

3. The optimal reanalysis scheme will vary depending on the application intended; for example, quite different restrictions would apply to input data for optimally estimating the weather pattern at an instant of time vs. optimally estimating climate change.

4. In studies of detection and attribution of climate change in the Arctic, it is important to recognize the differences between the observed surface warmings of 1925–1945 and of 1970–2000 respectively.

Co-chairs: **Volker Rachold** Alfred Wegener Institute, **Steven M. Solomon** Natural Resources Canada

The abstracts from the talks and posters presented during the Coastal Processes session can be found on pages 153–171.

The coastal zone is the interface through which land-ocean exchanges in the Arctic are mediated, and it is the site of most of the human activity that occurs at high latitudes. The arctic coastlines are highly variable, and their dynamics are a function of environmental forcing (wind, waves, sea-level changes, sea ice, etc.), geology, permafrost and its ground-ice content, and morphodynamic behavior of the coast. Environmental forcing initiates processes such as degradation of coastal permafrost and sediment transport by waves, currents, and sea ice (Figure 1). The coastal response (erosion or accretion) to these processes results in land and habitat loss or gain and thus affects biological and human systems.

Coastal processes in the Arctic are strongly controlled by regional phenomena, such as the sea-ice cover and the existence of onshore and offshore permafrost. During the prolonged winter season, the thick and extensive sea-ice cover protects the coastline from hydrodynamic forcing. During the open water season, sea ice is an important transport agent for coastal sediments. The coastal zone also marks the transition between onshore and offshore permafrost. During the short ice-free period, the unlithified ice-rich, permafrost-dominated coastlines can be rapidly eroded (at rates of up to several meters per year); the resulting coastal sediment, organic carbon, and nutrient fluxes play an important role in the material budget of the Arctic Ocean. Degradation of permafrost also releases trapped greenhouse gases (GHG).

Global and regional climate changes will significantly affect physical processes, biodiversity, and socio-economic development in arctic coastal areas. Additionally, arctic coastal changes are likely to play a role in global systems via feedbacks through the material flux generated by eroding coasts and the GHG emission from degrading coastal permafrost (Figure 2). Thus, the overall scientific goals of arctic coastal research are to:

- identify and understand the key processes controlling arctic coastal dynamics and their impacts on human systems, biology, and ecosystems;
- decipher and quantitatively assess the role of arctic coasts in the global system, including estimates of coastal retreat, material flux, and GHG emission from permafrost degradation; and
- establish models to predict the future behavior of the arctic coastal region in response to climate and sea-level changes.

The presentations of the coastal session at the SEARCH meeting have been grouped into three broad topics:

- overviews of international programs and initiatives,
- physical processes controlling arctic coastal dynamics, and
- impact and feedback of coastal material fluxes on arctic biogeochemical cycles.

Programs and Overviews

Significant efforts are underway to expand our understanding of arctic coastal processes. Arctic Coastal Dynamics (ACD) is a multi-disciplinary, multi-national project of the International Arctic Science Committee (IASC) and the International Permafrost Association (IPA); observations of coastal morphology, geology, and stability are the focus of ACD activities. Land-Shelf Interactions (LSI) is a new program under the Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE). Plans are underway to examine both biological and physical aspects of the arctic nearshore zone as part of the International Polar Year 2007–2008.

Physical Processes

These talks highlighted the coastal aspects of the arctic climate-cryospheric systems. Sea ice plays both destructive and constructive roles in the nearshore zone. Coastal processes occurring at high latitudes differ fundamentally from those at temperate latitudes because of the presence of ice (both ground ice and sea ice) and permafrost. Arctic coastal environments are poorly represented in observing systems. Improved observing networks and advances in understanding of coastal processes are critical steps towards developing predictive models of coastal response to changing climate.

Biogeochemical Processes

These papers engendered lively discussions about carbon input to the arctic seas and its ultimate fate. This highlights the uncertainty about the role of coasts in contributing to global carbon budgets, especially in the Arctic.

Conclusion

In summary, the session was a good starting point for focusing interest on coastal activities and issues. There remains a difficulty in developing better linkages between coastal researchers and those undertaking larger scale studies from a North Pole-centric perspective.

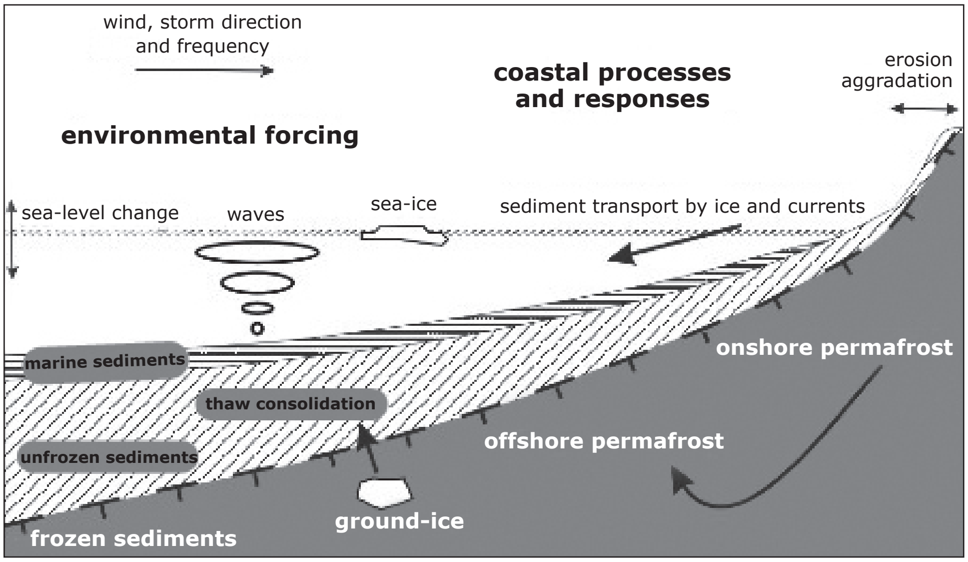

Figure 1. Arctic coastal processes and responses to environmental forcing.

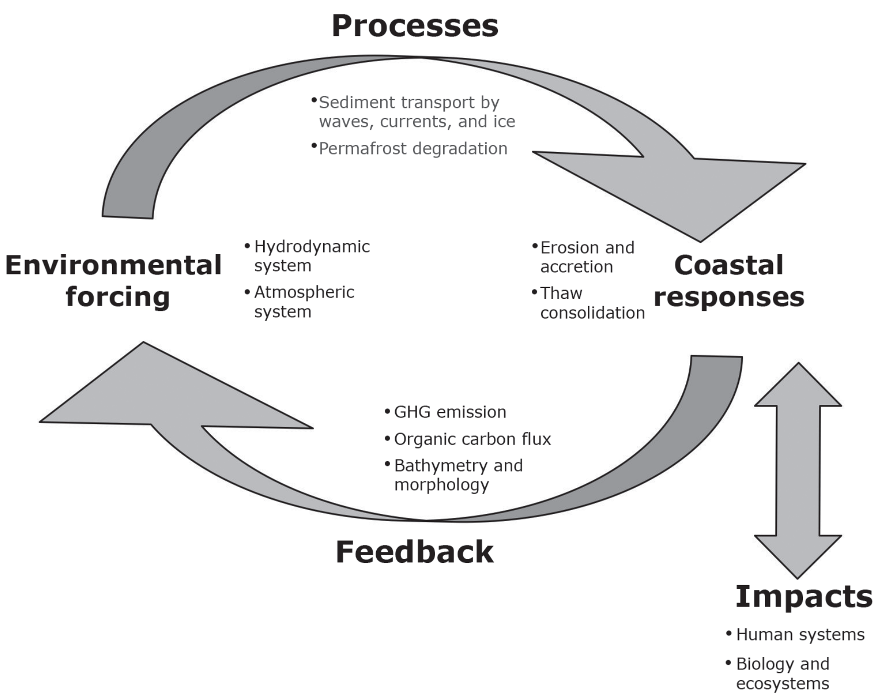

Figure 2. Environmental forcing, coastal processes and responses, impacts, and feedback.

Co-chairs: **Stewart Cohen** University of British Columbia and Environment Canada, **Matthew Berman** University of Alaska Anchorage

The abstracts from the talks and posters presented during the Social Feedbacks session can be found on pages 173–192. The session illustrated the intense interest in social feedbacks, as well as in methods for undertaking this research and the challenge of engaging northern peoples in a way that respects their wishes but also satisfies the needs of the research effort.

This session was divided into two sections:

- projects investigating adaptations to climate variations, and
- panel discussion on programs supporting research on social feedbacks.

Projects Investigating Adaptations to Climate Variations

Papers in this section addressed a variety of systems where human decisions interact with environmental change. Voinov et al. reported on a new U.S.-Russian research effort for one of the most developed and populated areas of the Arctic, the Imandra Lake watershed, which puts human dynamics within the framework of ecosystem change to integrate available information during a period of rapid economic change. Findings from Nicolson et al. suggest that the bowhead whale hunt at Barrow is highly affected by environmental conditions and that wind speed in the fall and wind direction and ice cover in the spring are the principal variables affecting whale-hunting success; these results agree with hunters' predictions. Such variability in hunting conditions supports flexible hunting regulations that allow for hunting failures (due to environmental factors) during some seasons. Hamilton explained how large-scale environmental changes involving the North Atlantic Oscillation (NAO) and Arctic-origin Great Salinity Anomalies (GSAs) have affected fisheries-dependent societies across the northern Atlantic in recent decades and provided examples of recurring themes in ecosystem-society interactions.

Panel Discussion: Programs Supporting Research on Social Feedbacks

During the panel discussion, participants were asked their views on methods for integrating community knowledge into assessments of larger issues (e.g., environmental change), the role of northern-based organizations, and written protocols while working within indigenous communities.

The panelists (see page 320) indicated that the use of formal protocols varies according to context and individual circumstances. In some cases, volunteer arrangements work because trust has been established between the parties. In others, a formalized process is needed, including specific agreements on data collection, access, and release of information to the public. Concern about the variability of data quality may lead to some formal arrangements to ensure quality control and, in some cases, to provide honorariums for participants. Some institutions may have difficulties working with protocols, but without them there may be legal challenges to releasing study information. As new generations of researchers and local people become involved, the type and rate of knowledge exchange will change. Northern communities value this. Also, many people in the North have local knowledge because of their living and work experience.

An example of "talking circles" illustrated how researchers and native peoples could be brought together to share views on environmental stresses, other stresses, study and data needs, and adaptive/coping actions that could be considered. This would complement the use of interviews, surveys, and other dialogue and data gathering methods.

The audience raised a number of questions and comments. Panelist responses are indicated in italics below each question.

Why not discuss social research with members of indigenous communities present in the session room?

> *Researchers who work with northern peoples may not have the resources that are needed to bring northern peoples to meetings outside of the North. Timing is also a challenge. If resources are not provided for this purpose, it may be easier to have these discussions in the North.*

How should traditional knowledge (TK) be used? There are concerns that this could be used out of the context from which it was offered. Northern peoples (e.g., Native Alaskans) should decide how it is distributed and used.

> *Different projects have different goals. Some projects are not really gathering TK, but "local" knowledge. Different methods are needed that fit the circumstances.*

How will ArcticNet involve Inuit organizations?

> *We are starting by establishing contacts with major organizations such as the Inuit Circumpolar Conference (ICC) and the Inuit Tapiriit Kanatami (ITK) and asking for their suggestions.*

Adaptation to change is not new. Why is change a negative thing? When does change become a crisis?

> *Change becomes a crisis when people cannot cope with it, but this will vary between communities. Good mechanisms for information exchange are needed to avoid crises.*

Additionally, participants discussed the relationship between scientific modeling and community concerns, problems with intellectual property rights to traditional knowledge, and the need to link research to the needs of decision-making agencies.

Co-chairs: **Joshua Schimel** University of California Santa Barbara, **Sue Moore** National Oceanic and Atmospheric Administration

Changes in arctic climate are often dynamic because they are amplified through complex feedback systems that involve both physical and biotic systems. To effectively document environmental changes in the Arctic, critical feedbacks that drive the climate system must be identified. The current state of science, including availability of empirical data and modeling approaches to biological feedbacks associated with arctic climate change, was the focus of this session. Two questions were central to the session theme:

- How do terrestrial ecosystem processes feedback to the arctic climate system?
- How are marine ecosystems linked to the Arctic's variable climate system?

Investigators presented findings using a number of approaches, including experimental manipulations, modeling, and case studies. The presentations and discussions

- verified that many of the biological feedbacks operating in arctic systems are positive, with potential to accelerate change or trigger abrupt, non-linear climate system behavior; and
- demonstrated the tremendous complexity, specificity, and variability which characterize biological feedbacks, making these multifactorial systems challenging to model and predict.

The abstracts for the talks and posters presented during the Biological Feedbacks session can be found on pages 193–216. Many of these topics also overlap with studies presented in the Changes on Land (pages 19–72) and Changes in the Sea (pages 73–132) sessions.

Terrestrial Feedbacks

Feedbacks between terrestrial ecosystems and the climate system involve at least three important mechanisms. First is the direct albedo effect on the arctic radiation budget; this is mediated through changes in both snow cover and vegetation. Second is through heat and water exchange with the atmosphere. Third is through trace gas emissions (CO_2, CH_4). The first two directly affect local to regional climate, while trace gases have their influence at the global level. In terms of regional importance, the albedo effect has been the most prominent to date, as the snow-free season has been getting dramatically longer in recent decades. The other two mechanisms, however, involve positive feedback loops that may magnify their importance over time, and the potential effects on climate systems are large. They may also have lag effects through changing vegetation structure, particularly the conversion of open tussock tundra to shrub tundra.

In terms of carbon cycling, tundra has acted as a long-term carbon sink, sequestering atmospheric carbon in soils that today contain approximately 11% of total world soil carbon. Decomposition, however, could release that carbon to the atmosphere, driving a positive feedback. Investigations of terrestrial biogeochemical cycles reveal the complex interactions among changes in composition and structure of terrestrial ecosystems, soil organic carbon, ecosystem carbon exchange, nutrient availability, soil temperature patterns, and disturbances such as fire or surface perturbation. Understanding the links between ecosystems, regional climate, and global climate requires spatially and temporally explicit process-based modeling and consideration of seasonal controls over trace gas and energy exchange, such as soil moisture (see Figure). Paleoenvironmental records can document past patterns and causes of ecosystem change.

Marine Ecosystems

We note that modeling in marine ecosystems are not as advanced as for terrestrial systems, resulting in a greater reliance on conceptual models based upon case studies.

Feedbacks among marine biogeochemistry, sea ice biomass dynamics, and primary production were explored in several papers. Stable isotope studies of the trophic structure of a deep benthic community suggest that the link between pelagic/sea ice organisms and the benthos is through sinking of grazers and their products (e.g., fecal pellets, molts, dead animals) to the seafloor rather than through direct coupling of algal material to the benthos. A novel in situ technique for estimating autotrophic biomass in sea ice revealed details of the seasonal pattern of algal growth inside fast ice and should improve future investigations of feedback mechanisms between arctic climate, marine food webs, and biogeochemical fluxes.

Case Studies of Indicator Species

Several case studies of indicator species, including marine mammals, seabirds, and fish, revealed complex effects of environmental change on demographics. For example, a long-term study (1975–2002) of black guillemots shows phenological and demographic sensitivity to the winter mode of the Arctic Oscillation (AO). A positive winter AO was associated with earlier snowmelt that leads to earlier access to nesting cavities for egg laying. Of note, the positive winter AOs in the 1990s correlated with a ~50% decline in the breeding population, likely due to a reduction in pack ice, the preferred guillemot foraging habitat. Newborn ringed seal pups depend on the integrity of snow lairs for protection from cold exposure and predation. Increasingly early snow melts associated with climate change can negatively impact ringed seal populations through increased juvenile mortality. A long-term study (1955–2000) of Bristol Bay sockeye salmon populations revealed that growth at sea was strongly associated with climate and salmon survival. The 1976–77 marine climate shift resulted in higher prey production and greater early marine growth in salmon, while the 1997–98 El Niño was associated with significantly smaller adult fish and lower survival. Finally, it was noted that climate change in the Arctic is regional. In contrast to the "western" Arctic, sea ice offshore of west Greenland increased between 1978–2001, resulting in a reduction in open-water refugia for sea bird and marine mammal species. Of the indicator species, narwhals are among the most vulnerable due to high site fidelity in Baffin Bay, where the entire population (> 50,000 whales) overwinters in dense pack ice.

Conclusions

Current studies of biological feedbacks in arctic systems reveal the marked complexity and variability of these systems and, in many cases, their potentially powerful positive amplification of climate and other environmental changes. Long-term observations need to be linked with appropriate process studies and modeling efforts to investigate these feedbacks and predict the implications for arctic ecosystems and the global system.

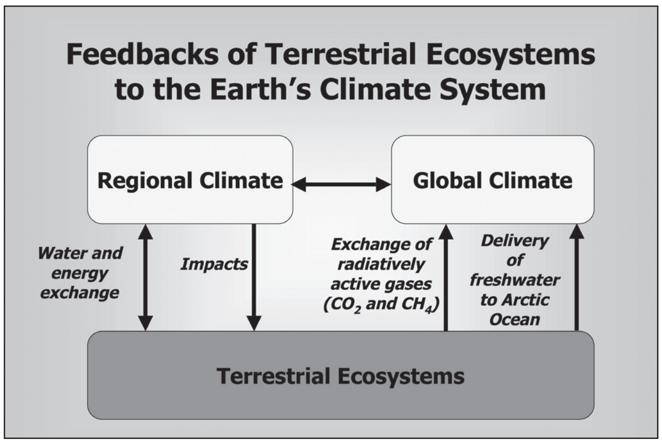

Figure. Feedbacks of the terrestrial ecosystems to the Earth's climate system. From McGuire et al.

Co-chairs: **Michael Steele** University of Washington, **Stephen Vavrus** University of Wisconsin

The abstracts from the talks and posters presented during the Physical Feedbacks session can be found on pages 217–239.

This session focused on a number of climatic processes either known or suspected to be important for shaping the future arctic environment. Many of these feedbacks may already be operating and could be affecting recent changes observed in the Arctic. These interactions include:

- the snow/ice-albedo feedback,
- changes in atmospheric and sea ice/ocean circulation,
- cloud feedbacks, and
- chemical/biological interactions with the ice and atmosphere.

Snow/Ice-Albedo Feedback

Several presentations identified aspects of the snow/ice-albedo feedback as being particularly important for enhancing climatic warming, including a longer duration of melt ponds on sea ice and greater solar absorption in the upper ocean. This seemingly straightforward positive feedback mechanism is complicated by findings such as Hall's modeling results showing that although the snow-albedo feedback behaves similarly under modern internal variability and greenhouse forcing, the sea ice-albedo feedback operates differently. Likewise, Perovich points out that the known relationship between low-albedo melt ponds and climate variability may differ in a much warmer climate, and this change may be "revolutionary, rather than evolutionary." Another complication is McPhee's new observational evidence showing that the enhanced bottom ice melting, due to greater solar absorption in the ice pack, is partially offset by the presence of fresh-water lenses that collect beneath floes.

All of these thermodynamic feedbacks will be affected by sea ice dynamics, which modify the snow/ice-albedo feedback by altering the amount, thickness, and distribution of ice cover. Any changes in sea ice or snow cover distribution are likely to have discernible ecological impacts, both for large species such as polar bears and caribou, as well as smaller organisms such as plankton. Humans may be directly affected by such changes; for example, the seasonal movements of large animals are likely to be impacted by alterations in the distribution of ice and snow cover. Furthermore, offshore resource development (e.g., oil) will be affected by reductions in sea ice cover, and shipping lanes may change in response to changing sea ice cover, possibly bringing more traffic to previously unaffected areas.

Atmospheric and Sea Ice/Ocean Circulation

Changes in the atmospheric and sea ice/ocean circulation also have the potential to either accelerate or weaken the rate of climate change in the Arctic. Most climate models predict greater atmospheric transport of energy into the Arctic under greenhouse warming, due to more water vapor transport (latent heat) in the moister atmosphere, thus providing even more high-latitude warming. Bitz and Vavrus point out that the details of such an increased energy import may be important, with regard to its seasonality, vertical distribution, and persistence. Contrary to this positive feedback, if atmospheric pressure decreases over the Arctic, as projected by most models (consistent with a more positive phase of the Arctic Oscillation), then a stronger flux of sea ice may develop from the Arctic Ocean into the North Atlantic, thus favoring a regional cooling and a possible weakening of the global thermohaline circulation. Most models predict a weakening of the thermohaline circulation, at least initially, in response to greenhouse warming. Unfortunately, Tremblay et al. show that simple correlations between sea ice flux through Fram Strait and atmospheric indices such as the North Atlantic Oscillation (NAO) show variations over time, making predictions of Arctic Ocean fresh water export difficult, even if the future behavior of the NAO were known.

Cloud Feedback

Another important but poorly understood process in arctic climate change is the cloud feedback, including changes in cloud amount and radiative characteristics. Although models differ even as to the sign of these changes in the future, recent model simulations by Vavrus suggest that cloud changes outside of the Arctic may be at least as important for affecting polar climate as local cloud changes within high latitudes. Furthermore, climatic conditions unique to polar regions mean that counterintuitive outcomes could result from changes in cloudiness. For example, whereas greater low cloud amount may contribute to cooling in most of the world, such a change may enhance warming in the Arctic due to the greater relative importance of polar clouds in trapping surface longwave radiation compared with reflecting shortwave radiation over the weak solar radiation regions of high latitudes. Increasing cloud amounts may impact humans and ecosystems via a reduction in direct solar energy, which may affect photosynthesis and the amount of harmful UV radiation that makes it to the Earth's surface.

Chemical/Biological Interactions

Complicating all of these physical feedbacks are indications that chemical/biological interactions between the cryosphere and atmosphere will play an important role in regulating arctic change. For example, Shepson et al. summarized recent field studies showing that there is significant photochemical species exchange between snow packs, sea ice, and the lower atmosphere that affects radiative transfer in the boundary layer. Similarly, Tjernström and Leck presented new findings that zooplankton in summertime leads within the ice pack produce biogenic cloud condensation nuclei that may regulate the abundance and radiative properties of polar clouds. Likewise, biological communities living in sea ice have been found to alter the partitioning of solar radiation at the ice-ocean interface, thereby affecting heat absorption in the upper ocean and ice floes. Any of these processes may be important yet unknown modifiers of physical changes within the polar climate system, but the uncertainty and potential ramifications increase if such chemical and biological feedbacks operate in concert. Many of these were discussed in a parallel session on biological feedbacks, including changes in and even disappearance of arctic species and ecosystems.

Conclusion

The global implications of projected arctic climate changes are considerable. Most of the feedbacks described in this session are positive and, therefore, have the potential to affect global climate either indirectly, by virtue of enhancing arctic warming, or directly, through modifying the meridional temperature/pressure gradient and therefore the dynamics of the climate system. In addition to the Arctic's projected rapid and amplified warming pattern in relation to the tropics and middle latitudes, the Arctic's response to greenhouse forcing is also likely to be much faster than that of the Antarctic region. Because the Arctic Ocean has a shallower oceanic mixed layer and a greater potential for a large albedo decrease compared with the Antarctic continent, which will maintain a bright surface even if enhanced surface melting occurs, the high latitudes of the Northern Hemisphere will probably experience the most extreme and rapid climate changes anywhere on Earth. Many of the feedbacks identified here are known to be or assumed to be occurring already in association with the warming trend in the Arctic in recent years (e.g., ice-albedo feedbacks). Because strong non-linearities and positive feedbacks are characteristic features of arctic climate, the northern polar regions have the potential for experiencing abrupt climatic changes and perhaps triggering rapid climate changes outside of the Arctic. The paleoclimate record shows that this region has undergone such abrupt changes in the past, and the source of the abruptness is often traced back to components of the cryosphere.

Session Summary: Drivers and Causes

Co-chairs: **James E. Overland** National Oceanic and Atmospheric Administration, **Mark C. Serreze** University of Colorado

The abstracts from the talks and posters presented during the Drivers and Causes session can be found on pages 241–255.

Key SEARCH hypotheses are that recent arctic changes are strongly linked to the Arctic Oscillation (AO) and are components of anthropogenic climate change. While the oral and poster presentations in the Drivers and Causes session provided many insights into the problem of arctic climate change, helping to address these hypotheses, it is clear much remains to be understood.

There is incontrovertible evidence that many of the observed changes have both direct and indirect links with the Arctic Oscillation (AO)—a large-scale mode of atmospheric variability that, in its simplest sense, can be viewed as an oscillation of atmospheric mass between the Arctic and middle latitudes. The AO changed from a strongly negative phase in the late 1960s and early 1970s to a strongly positive phase in the late 1980s to mid 1990s. Changes in the wind field and temperature advection patterns associated with this trend wind can explain much of the observed warming in the Arctic, especially for Eurasia, as well as regional cooling over parts of northeast North America. This atmospheric forcing also helps us understand changes in other variables, such as some aspects of the recent decline in arctic sea ice extent, changes in upper ocean circulation, regional trends in precipitation, and other alterations in the hydrologic cycle. Many changes appear to be occurring in biological systems, both for land and in the ocean, some of which also seem to have AO links.

Might this AO trend and associated arctic signals be simply a reflection of natural climate variability? We know that arctic warming of equal or even greater magnitude occurred in the 1930s. While the details of this earlier warming are difficult to assess, it is evident that arctic climate is intrinsically quite variable. Might the effects of the AO be superimposed upon a growing radiative forcing associated with greenhouse gas (GHG) loading? One supporting piece of evidence is that while the earlier 20th century warming was limited to high northern latitudes, the recent arctic warming is part of a global signal. Could GHG loading or other external forcing be favoring a higher frequency of the positive AO state, particularly through links with the stratosphere? While there is support for this from various climate model simulations, many uncertainties remain and no consensus has been reached. Better understanding the dynamics of the AO is obviously a key research priority. Many processes and interactions appear to be involved (see Figure).

It is also apparent that the AO framework has limitations. Many changes in the Arctic do not neatly fit into the paradigm and other atmospheric circulation patterns are known to have important impacts. Furthermore, while the upward AO trend from 1970 to the mid 1990s is certainly remarkable, the AO has regressed back toward a more neutral state in recent years. Yet the Arctic still appears to be warming.

Understanding arctic change requires improved climate models, as well as improved insights into oceanic processes from coupled ice-ocean models and observations. A number of presentations at the Drivers and Causes session articulated recent advances in these areas, as well as the many challenges that lie ahead. It is also clear that to understand the present requires that we better understand past behavior of the arctic system, such as during the Holocene thermal maximum. Hence the need to build upon our current suite of paleoclimate indicators.

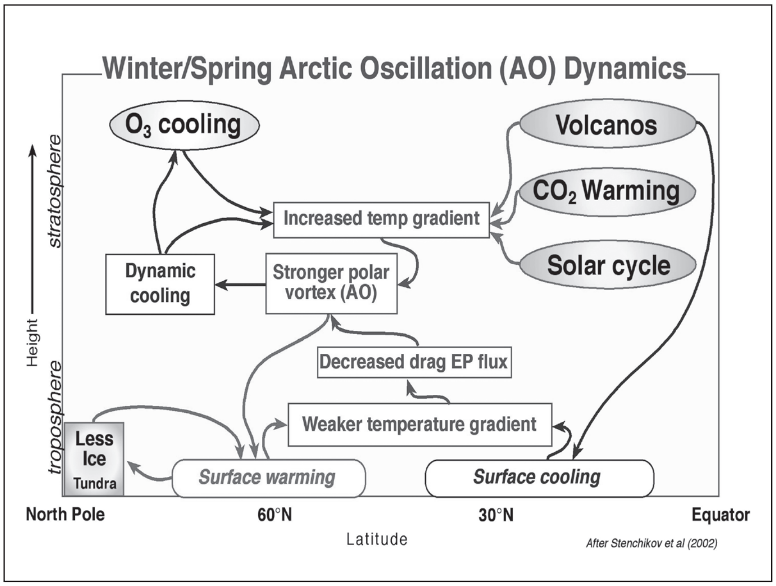

Figure. Winter/spring Arctic Oscillation dynamics.

The Early 20th Century Warming in the Arctic - A Possible Mechanism

Lennart Bengtsson Max-Planck-Institut für Meteorologie

The huge warming of the Arctic, which started in the early 1920s and lasted for almost two decades, is one of the most spectacular climate events of the 20th century. During the peak period 1930–40 the annually averaged temperature anomaly for the area 60°N–90°N amounted to some 1.7° C. Whether this event is an example of an internal climate mode or externally forced, such as by enhanced solar effects, is presently under debate. Here we suggest that natural variability is a likely cause where reduced sea ice cover is the main cause of the warming. A robust sea ice–air temperature relationship was demonstrated by a set of four simulations with the atmospheric ECHAM model forced with observed SST and sea ice concentrations. An analysis of the spatial characteristics of the observed early-century surface air temperature anomaly revealed that it was associated with similar sea ice variations. We have further investigated the variability of arctic surface temperature and sea ice cover by analyzing series of data from a coupled ocean-atmosphere model. By analyzing similar climate anomalies in the model, as occurred in the early 20th century, it was found that the temperature increase in the Arctic was caused by enhanced wind-driven oceanic inflow into the Barents Sea, with an associated sea ice retreat. The magnitude of the inflow is linked to the strength of westerlies into the Barents Sea. We propose a positive feedback sustaining the enhanced westerly winds by a cyclonic atmospheric circulation in the Barents Sea region created by a strong surface heat flux over the ice-free areas. Observational data suggest a similar series of events during the early 20th century arctic warming, including increasing westerly winds between Spitsbergen and the northernmost Norwegian coast, reduced sea ice, and enhanced cyclonic circulation over the Barents Sea. It is interesting to note that the increasing high-latitude westerly flow at this time was unrelated to the North Atlantic Oscillation, which, at the same time, was weakening.

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Terrestrial Arctic Change

F. Stuart Chapin, III University of Alaska Fairbanks

The polar regions are the cooling system for Planet Earth. Their effectiveness in dissipating heat has changed dramatically through time, with many of these changes occurring quite quickly. Recent changes in the Arctic suggest that this cooling system is becoming less effective, so changes occurring in the Arctic and elsewhere could have increasing impact on Earth's climate system. In the terrestrial Arctic, there is evidence for change in all major feedbacks that affect the climate system. Snowmelt is occurring earlier, creating a powerful positive feedback to summer warming. Carbon sequestration is changing, although the patterns are spatially and temporally complex, and the net effect is uncertain. Warming appears to have caused net carbon loss in dry areas and net carbon gain in wet areas. Indigenous and satellite observations suggest that the drying effects predominate. Arctic wetlands and lakes, which are the largest natural source of methane, may be increasing their production of methane, but again, the net effect depends on pan-arctic hydrologic change. Vegetation change (advancement of treeline and increased density of shrubs) is increasing energy absorption and local atmospheric heating. One consequence of this is warmer permafrost and increasing frequency of thermokarst, particularly after wildfire, which is becoming more widespread. The net effect of all these changes is an amplification of high-latitude warming.

What does this mean for people? It is a mixed bag. Arctic amplification of global warming will probably have net negative impacts at the global scale through effects on food and water supply. Within the Arctic, warming has complex effects on both industry and individual subsistence use. Warming of permafrost increases the cost and ecological impacts of infrastructure. Warming appears to have a net positive effect on caribou, resulting in near-historic peaks in most of the herds in North America and Russia, perhaps in part as a result of greater food availability and more favorable conditions on the calving grounds. Caribou, however, frequently reduce the viability of domestic reindeer herding. Changes in sea ice reduce access to marine mammals, and changes in weather patterns make weather less predictable to local hunters. Together these changes stress the capacity of local people to adapt to arctic change. The challenge for arctic science is to improve our understanding of the causal links among these events so we can project future trends with greater confidence and provide a more convincing case to the global public that human impacts on the climate system are already having negative impacts on human well-being that will likely become more severe with time.

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Findings of the Recent Arctic Climate Impact Assessment

Robert W. Corell American Meteorological Society and Harvard University

For the past four years, over 300 scientists and experts, including elders and other insightful residents, have worked on a comprehensive analysis, synthesis, and documentation of the impacts and consequences across the Arctic of climate variability and changes, including the impacts induced by increases in UV-B radiation. In 2000, the Arctic Council charged the Arctic Climate Impact Assessment (ACIA) to

- evaluate and synthesize knowledge of how climate and UV radiation have been changing in the Arctic, how they are projected to change in the future, and the likely impacts of those changes on environmental, human health, social, cultural, and economic systems, and
- provide useful information and recommendations to the governments, organizations, and peoples of the Arctic and the world to help them respond to the challenges and opportunities presented by climate change.

The Arctic Council tasked two of its working groups, the Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF), in association with the International Arctic Science Committee (IASC), to conduct the ACIA. All eight of the arctic nations and the U.K. provided financial and in-kind support. An Assessment Steering Committee (ASC) provided overall coordination for the ACIA and liaison with relevant national and international organizations, including indigenous peoples' groups and the Intergovernmental Panel on Climate Change (IPCC). The ACIA will provide information for the IPPC Fourth Assessment Report, to be completed in 2007. A meeting in August 2004 brought 11 Ministers of the Environment (representing seven arctic nations plus China, South Africa, the UK, and UNEP) to Svalbard to review preliminary results of the ACIA and discuss opportunities for research cooperation.

The assessment will produce two reports by November 2004:

- A scientific report, totaling more than 1200 pages in 18 chapters, subject to a comprehensive external review by an independent group of more than 225 international scientists and other experts;
- An overview report (about 140 pages), designed for a broad non-scientific readership and also externally reviewed.

In addition, the Arctic Council's Senior Arctic Officials are developing a policy document relating the reports' information to policy needs and providing recommendations for follow-up measures.

Changes in many sectors of the Arctic are being reported by both scientists and residents. The ACIA details and projects significant disruptive impacts from climate change and UV radiation in the Arctic, while identifying a number of potential opportunities for communities, economic sectors, and governments of the region. To develop its projections, the assessment used a single scenario of the future, the IPCC Special Report on Emissions Scenarios (SRES) B2 scenario. B2 is a "moderate" climate change scenario, which projects global CO2 emissions more than doubling, from about 6 GtC in 1990 to 14 GtC, by 2100. Under this scenario, nine Global Climate Models (GCMs) predict an average global temperature response of +2.2°C by 2071–2100 compared to 1961–1990. To provide model output to the ACIA, the B2 scenario was implemented on five GCMs; these GCMs predict approximately twice as much warming in the Arctic compared to the global average over a similar time period.

Evidence of recent warming in the Arctic includes records of increasing temperatures, melting glaciers, reductions in extent and thickness of sea ice, thawing permafrost, and rising sea level. Ozone depletion in northern latitudes and the resultant changes in UV radiation have increased markedly during the past decade, with some sectors of the Arctic experiencing short-term reductions in ozone of about 20% and increases of more than 40% in incident UV radiation. Over the past 30 years, arctic sea ice extent has decreased on average by about 10%, and this change has been 20% faster over the past two decades than over the past three decades. Projections that arctic sea ice extent and seasonal duration are likely to decrease even more rapidly in the future will lead to seasonal opening of potentially important marine transportation routes and significant changes in albedo, cloudiness, humidity, exchanges of heat and moisture, and ocean circulation. The average of the five ACIA model simulations project substantial and accelerating reductions in summertime sea ice around the entire Arctic Basin, with one model projecting an ice-free Arctic in the summer by the middle of this century.

The impacts will vary with regional differences in climate change and will depend largely on the interactions among the various changes; people's resilience or vulnerability to climate change depends on the cumulative stresses to which they are subjected as well as their capacity to adapt to these changes. Adaptation can involve changes in knowledge and how it is used, for example, using new weather prediction techniques. Arctic people have historically altered their activities in response to changing conditions; however, they increasingly indicate that the rapid rate of climate changes is limiting their capacities to adapt.

As the first effort to comprehensively examine climate change and its impacts in the arctic region, the ACIA represents the initiation of a process, rather than simply a set of reports. The ACIA brought together hundreds of scientists from around the world whose research focuses on the Arctic and incorporated the insights of indigenous peoples who have a long history of gathering knowledge in this region. Linking these different perspectives is an exciting process for both the science community and the residents of the Arctic, and it clearly has great potential to continue to improve our knowledge of climate change and its impacts.

For more information, see the ACIA website: www.acia.uaf.edu.

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The Nature, Measurement, and Modeling of Feedbacks

Judith A. Curry Georgia Institute of Technology

This talk provides some thoughts on framing the feedback issues for SEARCH and useful strategies for addressing these issues. "Feedback" is a $10 word with a very specific meaning, but it is often used to denote a forcing (rather than feedback) or to refer to any physical process (a "feedback process"). Such inappropriate uses of "feedback" in science and implementation plans can lead to confusion, untestable hypotheses, unachievable objectives, and ineffective strategies.

The Science Plan for the U.S. Climate Change Research Program is used as a reference point for considering the issue of feedback in the context of climate. Several examples are presented in the context of SEARCH on using the concept of feedback to design observing systems, model feedbacks, and assess the impact of imperfect models with feedbacks on decision making. "Feedback" should not be used as justification for endless process studies; feedback should only be used to justify process studies that include consideration of an appropriate selection of variables that are related conceptually in a complete feedback loop. Design of a long-term monitoring network should ideally include consideration of a variety of variables that are linked in conceptual feedback loops and that can be assimilated into models for a more complete representation of the system.

To illustrate the difficulties in attempting to appropriately model feedbacks in a climate model, an example is presented that illustrates the impact of various choices in the parameterization of sea ice albedo. Climate models have a large number of degrees of freedom and multiple and interconnected feedback loops; as a result, Monte Carlo (ensemble) prediction methods are needed to provide a quantitative measure of uncertainty. Coupling of submodels that interact nonlinearly adds considerable uncertainty to the model and most likely increases the need for larger model ensembles to provide useful predictions. This implies that there is a tradeoff in computing capacity to be considered in terms of increasing model complexity and adding additional subsystems, versus the size of the ensemble. Predictions based on ensembles can, in principle, provide far more useful information to decision makers than a single simulation that might provide a completely irrelevant picture of the future. A summary is given of recommendations regarding appropriate practices to utilize the concept of feedback for SEARCH.

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How Do Arctic and Subarctic Processes Interconnect? What Have We Learned?

Robert Dickson Centre for Environment, Fisheries, and Aquaculture Science[1], **Jens Meincke** University of Hamburg[2]

This talk is intended both to review major points of the OSM and to stimulate discussion on the interconnected nature of arctic-subarctic change and change processes. It is based on ten main statements:

1) The climatic forcing of arctic and sub-arctic seas in recent decades has been extreme; 2) Change can be imposed on the Arctic Ocean from the Nordic Seas; 3) Localized processes on the arctic shelves can drive extensive changes in the watermasses of the Arctic Ocean and north Greenland Sea; 4) We have experienced two episodes of arctic warming in recent decades, with quite different causes; 5) Arctic change can reach south to impose change on the Nordic Seas and on the deep/abyssal Atlantic; 6) The freshwater flux from the Arctic to the north Atlantic doesn't always get through; 7) There has been a major increase in the outflux of fresh water from arctic/sub-arctic seas over the past four decades, ultimately affecting the surface, intermediate, deep, and abyssal layers of the north Atlantic; 8) Paleo records suggest that freshwater irruptions to the northwest Atlantic have been associated with rapid changes in Atlantic climate, presumed to be due to an effect on the Meridional Overturning Circulation; 9) The recent freshening of our subarctic seas may not be merely a north Atlantic event, but the strong local expression of a change in the Global Water Cycle; 10) These changes on the scale of oceans and decades have been accompanied by massive changes in the great fisheries of sub-arctic seas.

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Spatial and Temporal Modes of Variability in Arctic Summer Temperature Over the Past 500 Years

Konrad A. Hughen Woods Hole Oceanographic Institution[1], **Peter Huybers** Massachusetts Institute of Technology[2], PARCS High-Resolution Working Group[3]

Spatial arrays of high-resolution (annual-decadal) paleoclimate records from throughout the Arctic can be used to distinguish different modes of variability and trace their behavior back in time. Previous compilations of primarily annual-resolution records from varved lake sediments, tree rings, ice cores, and marine sediments provided a view of average arctic summer temperature documenting dramatic 20th-century warming that ended the Little Ice Age in the Arctic and caused dramatic retreats of glaciers, melting of permafrost and sea ice, and alteration of terrestrial ecosystems. Some evidence suggests that these changes may be linked to a rising trend in the Arctic Oscillation (AO), and that the positive trend in the AO itself may theoretically be due to greenhouse warming. Unfortunately, combining records into a single arctic average does not exploit the valuable spatial information in the arctic-wide array, and cannot shed light on past AO behavior. A new international collaboration has created a high-resolution spatial array of arctic paleotemperature records for the past ~500 years. Annually resolved archives were used wherever possible (e.g., tree rings, varved lake sediments, and annual ice layers), but sub-decadal resolution records from ice cores and high deposition-rate lake sediments were included as well.

Empirical Orthogonal Function (EOF) analysis was used to characterize the spatial and temporal modes of variability contained in the proxy array. The leading modes of proxy variability all have highly significant correlations to leading modes identified in NCEP-NCAR reanalysis data, and thus are likely associated with dynamically significant processes, including: 1) a circum-arctic temperature trend with rapid 20th-century warming; 2) the Arctic Oscillation; and 3) a Urals Trough wave number three circulation pattern. Our analyses demonstrate the ability to identify the major modern observed modes of arctic SAT variability within an array of proxy data, and indicate the feasibility of of reconstructing these modes back in time. Analysis of this compilation of high-resolution arctic proxy data will provide insight into the long-term natural background variability of the AO, as well as other dynamic systems, and place observed recent positive trends into a pre-anthropogenic context.

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3. www.ncdc.noaa.gov/paleo/parcs

Inter-Annual Variability in Arctic Sea Ice Thickness from Space

Seymour Laxon University College London

Knowledge of the inter-annual variability in sea ice thickness is key to understanding both recent and future changes in arctic sea ice. The significance of trends in arctic sea ice drafts over the past few decades, using data gathered by intermittent submarine cruises, can only be determined though knowledge of the natural variability in ice thickness. Predictions of future changes in ice thickness also rely on properly representing the variability in ice thickness and the factors that control it. However, in situ data on ice thickness is insufficient to verify model simulations.

Here we present a time-series of sea ice thickness derived from satellite radar altimetry. We find that ice thickness is highly variable on inter-annual timescales and is controlled almost entirely by changes in the length of the summer melt season[1]. We also find that ice thickness during the past two winters has recovered to levels seen in 1993.

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How Does SEARCH Fit into the Larger Scheme of U.S. Climate Change Science?

James R. Mahoney National Oceanic and Atmospheric Administration

Significant focuses for evaluating climate change and variability include the high latitudes, high elevations, and transition and discontinuities zones – characteristics of the Arctic. The U.S. Climate Change Science Program (CCSP) recognizes the importance of incorporating arctic research in its quest for an improved understanding of climate change and its potential impacts.

The U.S. Global Change Research Program (USGCRP) was codified by the U.S. Congress in 1990. In June 2001, President Bush announced two new initiatives – the Climate Change Research Initiative (CCRI) and the Climate Change Technology Initiative (CCTI). In February 2002, he created a new cabinet-level management structure, the Committee on Climate Change Science and Technology Integration, to manage federal climate change research and technology development programs. The Climate Change Science Program (CCSP) is a key element of this new management structure and was created to integrate the work of the USGCRP and the CCRI. To accomplish this integration, the CCSP has subsumed both programs, with a single interagency committee responsible for the entire range of science projects sponsored by both programs.

The CCSP integrates the federal climate science research among 13 governmental agencies and has four areas of focus:

- Science—CCSP deals with ongoing science, including long-term studies and process studies;
- Observations and data—although a part of the science component, these are kept as a separate element to increase the attention paid to the need for observations and data for long-term analyses;
- Decision support—increasing attention given to “cross-walking” between the science and stakeholder communities; and
- Communication and education—dialogue to frame problems the CCSP is addressing.

The CCSP retains responsibility for compliance with the requirements of the Global Change Research Act of 1990, including its provisions for annual reporting of findings and short-term plans, scientific reviews by the National Academy of Sciences/National Research Council, and periodic publication of a ten-year strategic plan for the program.

A draft strategic plan for the CCSP was published in November 2002 and scientific and stakeholder comments were solicited through an international workshop, a written comment period, and a National Research Council review. The revised strategic plan was published in June 2003 and is currently being reviewed by the National Academy of Sciences.

The final U.S. Climate Change Science Program (CCSP) Strategic Plan will describe a strategy for developing knowledge of variability and change in climate and related environmental and human systems. In doing so, changes in the Arctic are explored throughout. For example, the CCSP Strategic Plan will call for 21 synthesis and assessment products to be developed within two to four years, one of which will assess past climate variability and change in the Arctic and at high latitudes. This report is significant in that high latitudes are especially sensitive and may provide early indications of climate change. Several other deliverables include Arctic research as well. Furthermore, Chapter 4 of the CCSP Strategic Plan, Climate Variability and Change, will pose several key questions to be addressed regarding environmental impacts of warming in the Arctic. As such, SEARCH long-term observations, modeling, process studies, and application analyses will be major contributions to the essential improvements needed for the comprehensive understanding and response to global climate change.

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SEARCH Vision and Core Hypotheses

James Morison University of Washington

The Study of Environmental Arctic Change (SEARCH) is motivated by observations indicating significant, interrelated, atmospheric, oceanic, and terrestrial changes have occurred in the Arctic in recent decades. During the early 1990s the influence of Atlantic water in the Arctic Ocean became more widespread and intense. The boundary between the eastern and western types of haloclines shifted from over the Lomonosov Ridge to roughly parallel to the Alpha and Mendeleyev ridges. The Atlantic water cores over the major ridge systems warmed. The observed shift in frontal positions corresponded with a change in sea ice drift. There has been a 3-4% per decade decrease in sea ice extent and a 43% reduction in central basin ice thickness in recent decades. Atmospheric pressure and circulation patterns changed consistent with an observed decrease in the annual mean sea level atmospheric pressure over the Arctic.

There have been changes on land as well. For example, changes in air temperature have been attended by reductions in spring snow cover. Arctic glaciers have exhibited negative mass balances, paralleling a global tendency. Various studies point to increased plant growth, increased fire frequency, and thawing and warming of permafrost. The physical changes are affecting ecosystems and society, impacting transportation, infrastructure, resource development, and food gathering. The changes appear to be part of an interrelated, panarctic complex which many of us have nicknamed Unaami (Siberian Yup'ik word for "tomorrow").

SEARCH is conceived as a broad interdisciplinary program of long-term observation, paleo and retrospective studies, analysis, and modeling with a core aim of understanding Unaami. We don't know Unaami's full extent or future course, but we think we can understand it because recent observations of the changing environment have given us new insights into how the arctic system functions. Multivariate analysis of many variables has quantified the notion of a complex of interrelated changes. We express the insights we have already gained, and our uncertainties, by framing four core SEARCH hypotheses. These are:

Unaami is related to a spin up of the atmospheric Polar Vortex. Several modeling studies and an observed relaxation of some of the changes toward climatology with recent decreases in Polar Vortex strength tend to support this hypothesis.

Unaami is a component of climate change. Because changes in the strength of the Polar Vortex (as indicated for example by the Arctic Oscillation index) represent a fundamental mode of atmospheric variability, Unaami is likely to be tied to climate change.

Feedbacks between the ocean, the land, and the atmosphere are critical to Unaami. Such feedbacks include those within the Arctic and global effects such as changing albedo and moderation of the global ocean overturning circulation.

The physical changes of Unaami have large impacts on the arctic ecosystems and society. This certainly appears to be true for the Arctic. Given the hypothesized connections with the atmospheric circulation of the Northern Hemisphere and with global climate, the impacts are potentially much broader.

The recognition of a systematic pattern of pan-arctic change and the formulation of these hypotheses exemplifies a change in the way many of us think about the arctic environment, and compel us to seek a systematic program of observation, analysis, and application to understand what is happening and respond appropriately.

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SEARCH Implementation: What Is Being Done and Where Are the Gaps?

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The Study of Environmental Arctic Change (SEARCH) has been conceived as a broad, interdisciplinary, multiscale program of long-term observations (including paleo and historical), analysis, and modeling, with a core aim of understanding the complex of significant, interrelated, pan-arctic changes that have occurred in recent decades (Unaami). This complex of changes is affecting every part of the arctic environment and is having repercussions on society.

The SEARCH Science Steering Committee (SSC), with support of the SEARCH Interagency Working Group (IWG), has the developed the *SEARCH Implementation Strategy Revision 1*, now available at http://psc.apl.washington.edu/search/index.html. It is meant to provide a more complete and specific strategy than provided in the SEARCH Science Plan. Community input has been sought through a number of workshops and community presentations. It is meant to be a living document that changes as we gain a greater understanding and improve our methods.

The Strategy includes a detailed list of activities required to address the SEARCH goals. The activities are grouped into eight activity areas:

- Arctic System Reanalysis (ASR) will assimilate data into models of various components of the arctic system to produce optimum estimates of key variables.
- Detecting and Quantifying Unaami (DQU) and Related Modes of Variability will use paleoclimate, historical, and archeological records as well as more recent observations to better define the scope of Unaami and its relation to other decadal modes of variability.
- Social and Economic Interactions (SEI) will examine the interactions of the physical and biological elements of Unaami with social and economic systems.
- Large-Scale Atmospheric Observatories (LAO) will make large-scale atmospheric observations

and include the use of several large land-based stations around the Arctic.

- Distributed Marine Observatories (DMO) will make large-scale atmospheric (surface), oceanographic, sea ice, and ecosystem observations in the marine environment.
- Distributed Terrestrial Observatories (DTO) will make large-scale atmospheric (surface), hydrological, glaciological, and ecosystem observations in the terrestrial environment.
- Linkages and Global Coupling (LGC) will use modeling and analysis to elucidate the connections between Unaami and global climate and the connections within the arctic system as they pertain to Unaami.
- Social Response (SOR) will research social and economic adaptation to climate change in the past and apply research on Unaami to economic and social concerns in the future.

Given the decline of several historically important observing systems, high priority should be given to continuing existing observational records while expanding to achieve spatial and temporal coverage consistent with the strategy. While it is recognized that new technology will improve our capability, the observational parts of the strategy (e.g., DQU, LAO, DMO, DTO) are designed to rely on the use of existing methods in a systematic way, with incremental improvement rather than requiring technical breakthroughs or unusual infrastructure.

The Arctic System Reanalysis is meant to combine observations and modeling to produce optimum estimates of important, but difficult-to-measure environmental variables such as precipitation minus evaporation or ice thickness distribution. This will involve applying data assimilation methods to parts of the arctic system where they have not been applied before. The immediate priorities for Detecting and Quantifying Unaami and Social and Economic Interactions will be to determine more clearly the scope of Unaami. The Linkages and Global Coupling activity area will examine two key hypotheses of SEARCH, that Unaami is related to global climate and that feedbacks within the arctic system are important to Unaami. To test these hypotheses, LGC will undertake analysis and modeling aimed at the various linkages within the arctic system and with global climate, areas that will build on ongoing work. The Social Response activity area will research social and economic adaptation to climate change in the past and apply research on Unaami to economic and social concerns in the future. To do this, connections with communities and industries will be gained by establishing a system of coordinated Local and Traditional Knowledge Co-ops and Community Data Networks. Generally, the SEARCH activities should include many existing activities and add to these to provide our descendents with the understanding and long-term records they will need to deal with a changing environment.

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Human-Environment Relations: Responding to the Challenges and Opportunities of Arctic Environmental Change

Mark Nuttall University of Alberta

Indigenous peoples throughout the Arctic maintain a strong connection and relationship to the environment through subsistence activities such as hunting, fishing, herding, and gathering. Climate variability and weather events often greatly affect the abundance and availability of wildlife and thus the opportunity for these people to harvest and process food. This longstanding dependence of contemporary indigenous societies on subsistence activities continues not only because of important nutritional benefits, but also because of significant social importance and cultural identity.

Successful long term adaptation of arctic indigenous peoples has been possible, in part, because of their adaptive capacity, that is, their social, cultural, and economic ways of responding and adjusting to climate variation and change. Such flexibility and versatility, however, is difficult today because of different social and economic settings. Indigenous people now live in permanent communities and retain formal economies along with traditional subsistence practices. Combined with the Arctic's natural vulnerability, this magnifies the potential affects of global climate change on indigenous peoples.

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Arctic System Synthesis: Is the Arctic Headed Toward a New State?

Jonathan Overpeck University of Arizona[1], **ARCSS Committee**[2], **ARCSS Synthesis retreat participants**[3]

The ARCSS Committee has been charged with the goal of drafting the next ARCSS Science Plan. For this reason, a process was put into place to result in a plan by the middle of 2004. There are many steps in this process, including community review. However, the first major step was to carry out an initial arctic-system synthesis.

The goal of this talk is to focus on the preliminary scientific results of the first ARCSS arctic system synthesis; this abstract provides the context. The synthesis itself was viewed as an experiment to 1) determine the value of synthesis to arctic environmental science, 2) begin uncovering the best way to carry out arctic synthesis, and 3) identify key arctic system unknowns. The synthesis was initiated during a week-long retreat of approximately twenty-five scientists (see team author list below) representing many of the major arctic-system disciplines. The format of the retreat was "adaptive," depending on the directions set by the participants. After several rounds of plenary discussion, the synthesis team decided to focus on a single big question, loosely defined as "Is the arctic system moving toward a new state, defined by significantly greater seasonally ice-free conditions?" The focus was on land ice (glaciers and ice caps), sea ice, and permafrost. Most of the retreat was then spent in a combination of long breakout-group discussions, punctuated by short plenary sessions. The focus was on defining the system and the state variables, as well as understanding the linkages between state variables (including those associated with the "ice" variables above, but also ecological, atmospheric, and human). An effort was made to identify the key feedbacks, both in terms of sign and magnitude, and also to comment on the impacts of possible future change. A consensus was reached that the arctic system is likely moving toward a new, more seasonally ice-free state in response to anthropogenic forcing, and that there are probably no large feedbacks that could prevent this change of state from occurring in the absence of reduced forcing. Current environmental change in the Arctic seems to support the possibility of a trajectory to a new arctic-system state. Moreover, the retreat identified several possible subsystem thresholds, beyond which the anticipated change of state could be difficult to stop or reverse. It is clear that human systems feed back on the rest of the system, often in a positive feedback sense. It also appears clear that the impacts of the state change would be large beyond just human systems, and that many of the impacts would be large, negative, and, in some cases (e.g., trace-gas fluxes and sea level change), global.

The participants of the first ARCSS arctic-system synthesis retreat were nearly unanimous in their belief that the synthesis was worth their time and effort, particularly given the complete absence of programmatic discussion. The ARCSS Committee is currently working on defining the nonprogrammatic process that will hopefully lead to several peer-reviewed products in 2004. It is also anticipated that the synthesis "experiment" will factor into the new ARCSS science plan, both in terms of what scientific gaps need to be filled, but also how arctic-system synthesis appears to be a powerful new approach for understanding how the system works, and how it will change in the future.

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Regional View: Perceptions and Concerns About Change

Caleb Pungowiyi Robert Aqqaluk Newlin Sr. Memorial Trust

In recent years, Alaska Natives in communities along the coast of the northern Bering and Chukchi Seas have observed substantial environmental changes. Residents in these communities intuitively expect these variances to eventually go back to normal; instead, however, these occurrences are becoming usual. This trend has completely altered residents' expectations concerning natural cycles and has negatively affected the quality of life for people who live a subsistence lifestyle and depend on wildlife resources. Indigenous observations of environmental changes include:

- Ice thickness and strength is decreasing. The number of accidents and deaths that occur from people falling through the ice has increased because they expect it to be thicker.
- Caribou migration is later due to warmer temperatures. In 2003, the migration was three weeks late and there were fewer animals in traditional migration routes. As a result, communities that depend on the herd must adjust their hunting habits accordingly.
- Low snowfall during the winter has changed breakup and the spring melt resulting in less ice scouring of river banks, which results in fewer young willows, and, ultimately, a decline in moose population. This created a hardship for residents that depend the animals for meat.

The strength and duration of these climate changes are also a concern. The impacts that environmental change will have on indigenous communities and their way of life have yet to be measured. Influences on the ecosystem, as well as the affected communities, need to be taken into consideration by scientists, game managers, and policy makers.

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Arctic Climate Simulations by Coupled Models

Annette Rinke Alfred Wegener Institute for Polar and Marine Research[1], **Klaus Dethloff** Alfred Wegener Institute for Polar and Marine Research[2]

The global coupled models differ significantly with respect to both magnitude and distribution of future changes predicted for the Arctic. An approach of model hierarchy and model ensembles is a powerful instrument for addressing the arctic climate and its variability. First, the performance of global coupled models is presented. Inappropriate parameterization of arctic processes and a coarse resolution are still the disadvantages of the global coupled models. An alternative approach is the regional climate modeling. The performance of atmospheric regional models is presented. First results of the Arctic Regional Climate Model Intercomparison Project are presented. The development of coupled regional models is still under way. Considering the pan-arctic domain, so far, only two models were applied for case studies. These results highlight the need for a deeper understanding of the atmosphere-ocean-sea ice interactions on the regional scale.

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Was Sea Ice Quite Thin in the 1990s? Yes.

D. Andrew Rothrock University of Washington

Submarine observations of sea ice draft from 1987 to 1996 show a decrease of about one meter over the eleven-year span. These data are digitally recorded by U.S. Navy submarines in a central (essentially the deep-water) half of the Arctic Ocean. All numbers here pertain to ice draft, which is about 0.89 of ice thickness. A comparison of average drafts over entire cruises with those from our sea ice model shows good agreement in the temporal change, with an rms discrepancy of 0.3 m. The spatial variation within cruises shows greater rms discrepancy—about 0.7 m, with modeled ice thicker than observed ice in the Beaufort Sea area and thinner near the North Pole.

We have reviewed papers in the literature of modeled inter-annual variations in thickness or ice volume. All models agree that thickness decreased by between 0.6 and 0.8 m from 1987 to 1996, but they tend to differ in their simulations of the 1950s to 1970s. Our model shows this decline in thickness in the 1990s over most of the Arctic Ocean; there is almost no offsetting increase near the Canadian Archipelago.

A regression analysis of these submarine draft data shows that about three quarters of the variance can be explained by three variants: an annual cycle with an amplitude of 1.1 m, a linear spatial gradient from the East Siberian Sea to Greenland of 0.8 m per thousand kilometers, and a downward trend of 0.07 m per year. This is perhaps the most satisfying method for isolating and estimating a trend from data of different cruise tracks in different seasons and different years.

Historical submarine ice-draft data can shed light on the records back to 1958. We show an inventory of all the submarine cruises for which draft data exist and are being processed and declassified.

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Inter-annual Variations of Polar Climate: Relationships to Annual Modes

Murry Salby University of Colorado

The atmospheric circulation varies from one year to the next, involving time scales of a couple of years, as well as secular changes that operate coherently over decades. These inter-annual changes are pronounced over the polar caps. They are represented in the so-called annular modes, which derive from the leading EOF of sea level pressure: the Northern Annular Mode (NAM) and Southern Annular Mode (SAM). Related to the Arctic Oscillation, and its counterpart over the Antarctic, the NAM and SAM describe variability that operates coherently from stratospheric levels down into the troposphere.

I will present an overview of annular modes, along with their involvement in intra-seasonal changes and long-term trends. Such behavior will be shown to bear a close relationship to changes of the residual mean circulation of the stratosphere. Comprised of downwelling over the winter pole and upwelling that compensates it at subpolar latitudes, the residual circulation is coupled to the troposphere through mass continuity. It is forced by momentum that is transmitted upward from the troposphere by planetary waves. Changes operating coherently with the residual circulation have the same basic structure as the NAM and SAM. They reflect changes over the Arctic, as well as coherent changes in the storm tracks. Such changes account for nearly all of the inter-annual variance of arctic temperature, even during unusually cold winters. A similar conclusion holds for wintertime ozone, which, like temperature, is regulated by the residual circulation.

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Natural and Anthropogenic Drivers of Arctic Environmental Change

Gavin A. Schmidt Columbia University

Changes to the composition of the atmosphere either from trace gases or aerosols affect the radiation budget globally and in the Arctic. Some of the changes are natural (solar variability, volcanic aerosols) while some are anthropogenic (greenhouse gases [CO_2, CH_4 etc.], sulfate aerosols, etc.). The radiative forcing of climate from each of these changes is discussed. Model simulations using these forcings as a function of time do well in estimating the rate of change of surface, tropospheric and stratospheric temperatures, as well as the decline in sea ice extent seen over the past 50 years. However, the Arctic may be uniquely sensitive to particular forcings, in particular, black carbon aerosols. These aerosols within snow have the potential to significantly lower snow albedo, and thus have an effect in high latitudes over and above their impact on atmospheric absorption. We also discuss the possibility that arctic climate can be forced dynamically by shifts in atmospheric circulation induced by radiative forcings acting predominantly at lower latitudes.

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Drivers and Causes of Arctic Environmental Change

Mark C. Serreze University of Colorado

Of the various environmental changes that have been observed over northern high latitudes in recent decades, the most obvious are pronounced rises in winter and spring surface-air temperature over sub-arctic land areas, reductions in sea ice extent and thickness, and warming and increased areal extent of the Arctic Ocean's Atlantic layer. Other studies point to increased river discharge, regional changes in precipitation, warming of soils and permafrost, increased shrubbiness, and altered cloud cover. For many of these changes, there is overwhelming evidence of strong links with increasing dominance of the positive phases of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). The AO/NAO are natural modes of atmospheric variability, and there is debate as to whether they are separate phenomena. Some modeling studies point to the recent AO/NAO trend as a reflection of inter-decadal climate variability. Other studies lend credence to the view that it is unusual and may be a response to changes in greenhouse gases.

Although the AO/NAO provides a useful coordinating framework, linkages with many aspects of change appear to be complex, indirect, or weak. For example, AO/NAO links with precipitation and net precipitation over the major Eurasian watersheds that could help explain changes in annual river discharge are not especially strong. Part of the problem may be the inherent difficulty in accurately measuring precipitation. There have been notable increases in winter discharge from the Yenisey and Lena. There is some evidence of a link with changes in ground ice and active-layer depth. On the other hand, recent work has shown that the direct human effects of diversions and impoundments are significant. While there is a demonstrated relationship between the winter AO and subsequent summer sea ice conditions, variability in the summer circulation is also important. A good case study is provided by the record low sea ice conditions observed in 2002. Some changes, such as in cloud cover, are puzzling. It appears that while arctic cloud cover has decreased during winter, it has increased during summer.

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The Freshwater Cycle and its Role in the Pan-Arctic System: Contributions from the NSF-Freshwater Initiative

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There is extensive and mounting evidence that the contemporary environment of the high north is changing and doing so over a broad, pan-arctic domain. Water is central to the functioning of the climate, hydrology, heat balance, biology and biogeochemistry of the Arctic and is thus of critical importance to human society. Thus, arctic environmental change must necessarily encompass changes to the hydrology of the region. Productivity, carbon balance, energy balance—in particular evapotranspiration—and hence runoff, are all coupled closely and will be affected by the combined changes in temperature and precipitation.

Over decadal time scales the stature and relative abundance of plants may be changing as well, producing new patterns of feedback to the climate system by altering regional-to-global scale energy and carbon balances. Increases in freshwater transport to the Arctic Ocean are now clearly documented and may at some point reduce the formation of North Atlantic Deep Water, resulting in a cooling in the North Atlantic region. These changes have enormous biogeophysical consequences that in turn make them critical to society and sound policy-making.

NSF recently created the Pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP), whose mission is to seek a better understanding of arctic hydrology and the natural linkages of hydrology with closely related atmospheric, terrestrial, and oceanic processes and cycles. An allied effort, the Arctic Freshwater Initiative (FWI), represents one of NSF's contributions to the SEARCH initiative. FWI, whose synthesis activities are being coordinated through Arctic-CHAMP, brings together atmospheric, terrestrial, and oceanic researchers to study the sources and fates of variations in the pan-arctic freshwater cycle. A review of the status of these programs and how they are contributing toward a better articulation of arctic environmental change through SEARCH will be offered.

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Inuit and Climate Change: Influencing the Global Agenda

Sheila Watt-Cloutier Inuit Circumpolar Conference

Models of global climate change project particularly severe impacts in high latitudes—the homeland of Inuit and other indigenous peoples. The draft Arctic Climate Impact Assessment (ACIA) being prepared under the eight-nation Arctic Council will be presented to ministers of foreign affairs in September 2004. Prepared with the full co-operation of six indigenous peoples' organizations—"permanent participants"—in the council, the assessment is likely to conclude that marine mammals will have substantial difficulty adapting to the impacts of climate change. So will Inuit.

When discussing globally the impacts of climate change in the Arctic we need to put a human face to the issue. It is of central importance that the ACIA be used to promote substantial reduction in emission of greenhouse gases that contribute to global climate change, and that indigenous peoples and all northerners have the tools, budgets, institutions, and other resources needed if they are to adapt to the inevitable. The Inuit Circumpolar Conference is committed to using the ACIA to promote policy responses that will protect the ways of life of Inuit.

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CHANGES ON LAND: PRESENTATIONS

The Response of the Alaskan Boreal Forest to a Warming Climate

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The Alaska boreal forest is one of the largest forest regions in the U.S., is largely free of human disturbance, and has experienced a major climate warming since the 1970s. In Alaska, black spruce-dominated stands are the dominant forest-cover type, making up about 55% of the boreal forest, followed by white spruce at about 25%, and birch-dominated stands at 14%. Tree disks and cores from black and white spruce and birch were collected throughout interior Alaska to determine climate sensitivity and potential for carbon credits and storage. We also include information from white spruce cores collected in the Brooks and Alaska Ranges. Interior Alaskan low-elevation upland white spruce show a consistent negative radial growth response to summer temperature, but black spruce and birch show varied responses. Growth of different populations of black spruce is correlated with several different climate factors, and the relationships are statistically strong enough that excellent predictive relationships can be developed. Growth of slope and ridgetop black spruce is negatively related to early and late summer temperatures at Fairbanks; the trees grow best in cool summers and least in warm summers. Growth of valley-bottom black spruce on permafrost is either positive to winter temperature or negative to early spring (April) temperature. Growth of black spruce on Tanana Valley surfaces near Fairbanks responds positively to midwinter temperatures. Radial growth of birch on south-facing slopes near Fairbanks is highly negatively correlated with summer temperature. Growth of older birch on an east-facing slope in Bonanza Creek LTER is positively correlated with individual summer months over a three-year period. Future growth of boreal tree species, derived from these empirical relationships with past temperature, have been developed for five GCM scenarios including the Canadian Climate Center and Hadley Center models. Model results for monthly variables for the Fairbanks grid cell for 2001–2099 were calibrated from the 1990–2000 period of overlap. Although all models produced increasing warmth, some failed to reproduce variability consistent with recorded data, and some produced systematic divergence in seasonal temperatures not present in the recorded data. The models produce climates indicating that some populations of at least two of the tree species would not survive, because rates of growth would approach zero within 70–100 years.

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GTN-P Monitoring Network: Detection of a 3 K Permafrost Warming In Northern Alaska During the 1990s

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The GCOS steering committee recently (1999) approved the development of a globally comprehensive permafrost network to detect temporal changes in the solid-earth component of the cryosphere. The International Permafrost Association (IPA) immediately took responsibility for managing and implementing the Global Terrestrial Network for Permafrost (GTN-P), as part of the Global Terrestrial Observing System (GTOS). GTN-P has two primary observational components: 1) the permafrost's active-layer, and 2) the thermal state of the underlying permafrost. Active-layer monitoring is generally accomplished using automated surface instrumentation while the thermal state of deeper permafrost is determined through periodic temperature measurements in boreholes. Thirteen countries are currently involved in this effort.

In this paper, we focus on the portion of the GTN-P network contributed by the U.S. Department of the Interior. DOI participates in both aspects of GTN-P with active-layer monitoring stations spanning northern Alaska and a 21-element deep borehole array in the National Petroleum Reserve Alaska (NPRA). The first stations in the active-layer network were installed during 1998. Although the records from the AL network are still too short to identify trends, anomalous periods can already be identified. The AL network records also provide a basis for understanding signals detected in the deep borehole array. The DOI/GTN-P borehole array is the largest array of deep boreholes in the world currently available for monitoring the thermal state of deep permafrost. Periodic temperature measurements in the boreholes began in the late 1970s, soon after the array was drilled. Near-surface temperature fluctuations across the array were generally small during the 1980s, except for a short cold period during 1983–84. The situation changed dramatically during the 1990s.

Beginning in 1989, coincident with a large change in the Northern Hemisphere Annular Mode (NAM), temperatures began warming across the array. By 2002, near-surface permafrost temperatures had warmed an average of 3 K (mean-annual) across the array relative to 1989; during this period, permafrost temperatures along the coast warmed 1–2 K while those at some interior sites had warmed 4–5 K. Records from the active-layer network (beginning 1998) show a strong sensitivity of permafrost temperatures to the thickness and duration of the seasonal snowpack. At this point, it is unclear how much of the warming detected in the boreholes during the 1990s was due to air temperature changes and how much is due to changes in the seasonal snowpack. Comparison with other records may provide the answer.

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Atmosphere-Ocean Teleconnections and Alaskan Forest Fires

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The boreal forest is a huge biome that contains large stores of carbon. Most aspects of ecosystem dynamics in the boreal forest are controlled by wild fires, but the drivers of the fire regime are poorly understood. Some researchers suggest that the fire regime is modulated by the vegetation in the course of decade-scale cycles of secondary succession, and at millennial time scales by changes in tree species abundances. Others think regional climate is the dominant driver of the fire regime. Here we use a multiple linear regression model to quantify relationships between climatic variables and the annual area burned in Alaska over the past fifty years. The seasonality of the circulation-fire linkage is addressed through a systematic evaluation of the East Pacific teleconnection field keyed to an annual fire index. The impacts of ocean-atmosphere interactions are examined through the use of equatorial sea surface temperatures as explanatory variables in the regression model. Six explanatory variables and an interaction term collectively explain over 80% of the variability in the natural logarithm of the number of hectares burned annually in Alaska from A.D. 1952 to 2002. Results reveal that tropical sea surface temperatures and the East Pacific teleconnection (EPT) exert an influence on short-term climate and weather in Alaska. Strong positive phases of the EPT are associated with upper airflow that is more meridional in nature. This meridional flow is conducive to the development of mid-troposphere anomalies that affect short-term weather and fire behavior. Negative phases of the EPT are associated with strengthened westerlies in the eastern North Pacific as a consequence of a more zonal upper airflow. The shift in sign of the teleconnection over a period of several months exerts a significant signal on both temperature and precipitation during the spring and summer in Interior Alaska, while SST anomalies exert an influence on snow pack development through influences on October and November precipitation. These results suggest that climate is an important driver of the fire regime in the boreal forest; however, there is more to fire regime than the number of hectares burned. Lacustrine records of charcoal and observations on the interactions between fuel type and fire behavior all suggest that there are important biological feedbacks involved. We are currently exploring the rich behavior that results when climate drivers are linked to vegetation dynamics in a landscape-scale model of ecosystem dynamics.

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The Contribution of Alaska's Glaciers to Global Sea Level Rise

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Student Poster

We have used laser altimetry to measure surface profiles of almost one hundred glaciers in Alaska and northwestern Canada. To date, seventy-two of these glacier profiles have been compared to USGS maps from the 1950s to calculate volume changes. The measured glaciers were grouped into seven regions, and volume changes extrapolated to all glaciers in these regions. All of the glacierized areas of Alaska are accounted for in the extrapolation. Data reduced so far show an average thickness change of -0.5 m a^{-1}, or 0.14 ± 0.04 mm a^{-1} sea level equivalent for the period from the 1950s to mid 1990s. Repeat profiles of forty-eight glaciers between the mid-1990s and 2000–01 suggest that the thinning rate has almost doubled in recent years. Our estimates represent the largest glaciological contribution to sea level rise yet measured.

Preliminary work on the effect of climate change on glacier mass balance shows that measured glacier changes can be explained by a summer warming of about 0.7° C, a value slightly greater than the observed temperature change of 0.4° C. We will discuss ways in which we are working to improve the definition of regions used in this study, the extrapolation from single glaciers to entire regions, and the extrapolation of thickness change along one or a few profiles to an entire glacier. We will also discuss "abnormal" glaciers, such as surging and tidewater glaciers, and remnant ice fields. Many tidewater glaciers have undergone rapid retreats in the past century, at a rate that is not typical for terrestrial glaciers of the same region. On the other hand, there are a few advancing tidewater glaciers surrounded by terrestrial glaciers with strongly negative mass balances.

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Arctic Change: Humans as Passengers and Drivers

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Key science questions for SEARCH include: 1) are humans merely affected by arctic change (passengers), or are we also causing it (drivers)?; 2) at what point do climate and environmental change issues become as important to the public as other socio-economic issues—like health and unemployment—that often dominate in the media?; 3) in addition to indigenous populations and subsistence or mixed economies, there are other human groups (e.g., tourists, non-native residents) and economies (e.g., heavy industry) that can serve as passengers and/or drivers. How should we think about these different groups? Will the effects on each of them be the same?

In terms of linking the natural, physical, and social sciences to answer these questions, we need to carefully address scale issues and, in particular, the patterns of recently observed ecological and social impacts. Just as not all sectors of the Arctic are currently experiencing a warming trend, there is a geography of anthropogenic drivers such as intensive and extensive land use. We now know that small-scale, low-intensity disturbances can be significant if they accumulate in space and time to achieve relevance at the regional scale. As startling as some of the reported ecosystem changes are, for many indigenous groups in northern Russia they pale next to the social and economic upheaval that has taken place since the collapse of the Soviet Union. The rapid and unfettered industrial development of the Russian Arctic contrasts with the more stringently regulated approach in North America.

In order to better characterize the effects of recent trends in high-latitude climate, it is necessary to understand not only the burgeoning raft of quantitative data on biophysical parameters, but also the arguably diminishing pool of traditional ecological or local knowledge. Qualitative data based on participatory approaches to research derive from a time slice of the past 30–50+ years, within the lifetime of active or retired people who have lived on the land and sea full-time or seasonally. Intimate ecological knowledge is not a universal among all northern peoples, just as not all SEARCH research questions may necessitate, or benefit from, stakeholder involvement. SEARCH can and should serve to enhance the dialogue between biophysical scientists, social scientists, and local stakeholders. Local knowledge in regions characterized by more widespread forms of land use can perhaps help to partition the effects of climate change from effects wrought by natural or managed shifts in the abundance and density of living resources.

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Historical Changes in Seasonal Freeze and Thaw Depths in Russia

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Seasonal freezing and thawing processes in cold regions play an exceedingly important role in ecosystem diversity, productivity, and the arctic hydrological system in general. Furthermore, long-term changes in seasonal freeze and thaw depths are important indicators of climate change. Only sparse observational historical measurements of seasonal freeze and thaw depths are available in permafrost and seasonally frozen ground regions. However, soil temperature data are more readily and widely measured.

Using mean monthly soil temperature data for 240 stations located throughout Russia for 1930–90, we have devised an interpolation method that determines the depth of the 0°C isotherm based on soil temperature data measured at various depths: 0.2 m, 0.4 m, 0.6 m, 0.8 m, 1.2 m, 1.6 m, 2.0 m, 2.4 m, and 3.2 m. This simple methodology works remarkably well and the relationship between the available measured annual maximum freeze and thaw depths and our interpolated values is almost perfectly 1:1, with a correlation coefficient (Pearson's R) greater than 0.97. Having verified the reliability of the interpolation methodology we are subsequently able to work with a greatly improved sample size of stations.

A comprehensive evaluation of these new data's long-term trends in Russia indicates that, in permafrost regions, active layer depths have been steadily increasing. In the period 1956–90, during which time sample sizes are large enough for statistical analysis, the active layer exhibited a statistically significant deepening by approximately 11 cm. The changes in the seasonally frozen ground areas are even greater—the depth of the freezing layer has exhibited a statistically significant decrease, resulting in 33 cm less frozen ground in 1990 than in 1956. In general these changes indicate that, as temperatures have been increasing globally in recent decades, permafrost is thawing to a greater depth during the warm season while less of the ground is freezing during the cold season. Potential direct consequences of these trends are increased river runoff and changes in discharge throughout the Russian Arctic drainage basin.

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Effects of Climate Change on Tundra Ecosystems

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Evidence of anthropogenically enhanced climate change continues to accumulate from polar regions. Responses of tundra ecosystems to the changes have shown strong variation at local to regional scales. For example, shrub cover has increased in parts of the Alaskan tundra and taiga, and increases in shrub cover have also been noted in experimental warming plots throughout the tundra biome, although large areas of high-arctic tundra have shown little change. Such a major change in the dominant functional group of these ecosystems (from low herbaceous to taller woody species) has important implications for feedbacks within the systems and to the atmosphere. Warming will cause changes in the carbon balance of tundra and taiga, which hold 25% of the soil carbon of global terrestrial ecosystems. However, trajectories of these changes are largely unknown for most northern systems and differ because of initial conditions of the carbon and nutrient economy.

While a considerable amount of experimental research has been conducted in tundra ecosystems to unravel the complex effects of environmental change on structure and function, much of the research has been spatially and temporally restricted. Processes and components respond to environmental changes at different rates: metabolic processes such as photosynthesis and respiration may respond in seconds to hours; allocation of nutrients and carbon within individual organisms may take hours to weeks; while changes in genetics and the abundance and diversity of organisms may take decades to centuries. Adding to this temporal complexity is the variation in ecosystem structure across gradients at local (e.g., moisture) to regional (e.g., latitude) scales. For example, we would expect important differences in species' responses to warming in open high-arctic environments, where conditions would be ameliorated, relative to their southern limits, and where increases in competition could result in negative responses. Clearly, there are no experimental approaches that can incorporate all of these temporal and spatial scales appropriately. Ecosystem models can provide tools to investigate potential effects of environmental change that incorporate processes at most scales, although the models themselves are based on the limitations of observational and experimental studies.

Some of the limitations can be overcome by conducting experimental studies along environmental gradients where the long-term adjustments to processes with slow time-constants can be compared across ecosystem types. In addition, maintaining these studies over sufficient time periods to allow for adjustment in ecosystem conditions greatly increases the value of the results. These approaches are incorporated in the International Tundra Experiment (ITEX), where similar environmental manipulations have been maintained for >10 years at sites throughout the circumarctic and in alpine tundra. Measurements of responses at the individual to ecosystem level have confirmed observations of change in northern Alaska, but have also pointed to regional differences in responses. Continued long-term research using coordinated networks such as ITEX will help to ensure that we capture important temporal and spatial variations in tundra ecosystem responses to climate variability and change. This will also help to improve modelling efforts to predict future response.

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Terrestrial Changes in Polar Regions: Evidence, Attribution, and Implications

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The effects of a warming climate on the terrestrial regions of the Arctic are already becoming apparent; some subsequent impacts are also becoming evident. It is expected that the effects and consequences of a warming climate will become even more evident within the next ten to fifty years. These changes will affect the Arctic Basin through impacts on regional weather, oceanic circulation patterns, salinity and temperature gradients, sea ice formation, and water properties. It is difficult to quantify the long-term effects of a changing climate, but it is possible to envision many of the changes that we should expect.

The broadest impacts to the terrestrial arctic regions will result through consequent effects of changing permafrost structure and extent. As the climate differentially warms in summer and winter, the permafrost will become warmer, the active layer (the layer of soil above the permafrost that annually experiences freeze and thaw) will become thicker, the lower boundary of permafrost will become shallower, and permafrost extent will decrease in area. These simple structural changes will affect every aspect of the surface water and energy balances. As the active layer thickens, there is greater storage capacity for soil moisture and greater lags and decays are introduced into the hydrologic response times to precipitation. When the frozen ground is very close to the surface, the stream and river discharge peaks are higher and the base flow is lower. As the active layer becomes thicker, the moisture storage capacity becomes greater and the lag time of runoff increases. As permafrost becomes thinner, there can be more connections between surface and subsurface water. As permafrost extent decreases, there is more infiltration to groundwater. This has significant impacts on large and small scales. The timing of stream runoff will change, reducing the percentage of continental runoff released during the summer and increasing the proportion of winter runoff. This is already becoming evident in Siberian rivers. As permafrost becomes thinner and is reduced in spatial extent, the proportions of groundwater in stream runoff will increase as the proportion of surface runoff decreases, increasing river alkalinity and electrical conductivity. This could impact mixing of fresh and saline waters, formation of the halocline, and seawater chemistry. Other important impacts will occur due to changing basin geomorphology. Currently the drainage networks in arctic watersheds are quite immature compared with the more well-developed stream networks of temperate regions. These stream channels are essentially frozen in place as the major flood events (predominantly snowmelt) occur when the soils and streambeds are frozen solid. As the active layer becomes thicker, significantly increased sediment loads will be delivered to the ocean. Presently, the winter ice cover on the smaller rivers and streams (<10,000 km^2) are completely frozen from the bed to the surface when spring melt is initiated. However, in lower sections of the rivers there are places where the channel is deep enough to prevent complete winter freezing. Break-up of the rivers differs dramatically in these places where the ice is not frozen fast to the bottom. Huge ice chunks are lifted by the flowing water, chewing up channels' bottoms and sides and introducing massive sediments into the spring runoff. As the air temperatures become higher and the active layer becomes thicker, we have reason to believe the surface soils will become drier. As the surface soils dry, the feedbacks to local and regional climate will change dramatically, with particular emphasis upon sensible and latent heat flux. This may impact recycling of precipitation, capabilities to predict weather, and may indeed increase variability of many processes and variables, including convective storms.

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Changes in the Environment and Ecology at Toolik Lake, Alaska.

John E. Hobbie Marine Biological Laboratory

Toolik Lake, on the North Slope of Alaska, is the site of a long-term ecological study of tundra, lakes, and streams that is now in its 28th year. It is expected that funding from the U.S. Long-term Ecological Research program will continue for decades more. Data collected include climate, thickness of active layer, water and soil temperatures, species and abundance of vegetation, primary production and chemistry in tundra, streams, and lakes, species and abundance of stream and lake invertebrates and fish, and growth of stream fish. Long-term experimental manipulations include warming, shading, and fertilizing four types of tundra, fertilizing streams and lakes, and changing the predation pressure from fish at the top of the trophic cascade. Simulation models based on mechanistic or process understanding are used to forecast and hindcast ecological response to changes in CO_2 concentrations, air temperature, and soil moisture.

The increase in air temperature of several degrees centigrade over the past decades in northern Alaska is well documented. Most of this is in winter-time temperatures. Permafrost temperatures have risen but some of the rise is due to changes in depth of snow. At a depth of 20 m, where the annual variation is damped out, the permafrost temperature is still –5° C so there is no thawing. The long-term response of the vegetation is subtle and has only in recent years begun to emerge from the variability across the landscape. The trend is for an increase in the abundance of shrubs, such as dwarf birch. The chemistry of streams and lakes is also changing; the alkalinity has doubled in the past decade. The most likely cause is increased total weathering of glacial till as the depth of the thawed layer increases slightly and material frozen for 10,000 years is exposed.

Long-term experiments with low-lying tundra vegetation give even more dramatic results. An increase of 5° C in air temperature led to the dominance of birch that reached a height of more than a meter. Similar results with fertilizer treatments indicate a possible link to rates of nutrient cycling. Long-term measures of fish growth in streams reveal that this population of arctic grayling is close to its upper limit of temperature for survival. If summer temperatures continue to increase, the grayling will burn more calories than they can collect in their food, they will lose weight during the summers (which happens in warm summers now), and will be unable to reproduce the following spring. If warm summers become more frequent, the population will not reproduce and may die out.

Models of tundra carbon are based on processes of photosynthesis and nitrogen cycling and calibrated to the long-term experimental data. The projection for the next century is that there will be a relatively small increase in carbon stored in soils and vegetation.

In conclusion, even in the arctic tundra where the first ecological changes to climate change are expected, the response of the environment and ecosystems is slow and difficult to measure even over three decades. A number of intensive study sites must be established in addition to the three or four already in existence.

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Eighteen Years of Vegetation Monitoring in the Arctic National Wildlife Refuge, Alaska

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Temperatures in northern Alaska have shown a warming trend over the past thirty years, so we expect that vegetation would be changing also. However, little evidence of recent vegetative changes measured on the ground exists for northern Alaska. This may be due mainly to the lack of permanent plots established before the warm 1990s. Also, year-to-year variability may mask long-term trends, and vegetation changes may lag behind climate changes.

Botanists from the Arctic Refuge in northeastern Alaska sampled twenty-six permanently marked vegetation plots five or six times between 1984 and 2002. The plots were the undisturbed controls from a study tracking recovery of winter seismic trails. They are the oldest permanent vegetation plots in the refuge and represent all of the major vegetation types on the coastal plain tundra of the refuge. We estimated percent cover of vascular and nonvascular plant species using point-sampling, lowering pins from a frame and recording species encountered. We also measured depth of the soil active layer and took photographs from permanent photo points. At four plots in riparian shrublands we measured height of the willows. Vegetation data were collected in 1984, 1985, 1986, 1988, 1991, and 2002. Active layer depth was measured in 1984, 1985, 1988, 1991, 1998, and 2002.

We examined results from the undisturbed control plots for evidence of change over time. We tested the common overall trends among plots using linear mixed-effects regression models. Models are still being refined, so results reported here are preliminary. We found small but statistically significant decreases in moss, liverwort, and lichen cover over the eighteen-year period. Depth of the soil active layer increased. No significant changes were detected in vascular plant cover or shrub height. The results are supported by data from other vegetation plots in the Arctic Refuge. At plots established between 1996 and 1998 and resampled five years later, cover of nonvascular plants declined at almost all plots while no trends were found for vascular plants.

Much of the year-to-year variability at our plots can be explained by temperature records from northern Alaska. Because of the lack of plant cover data between 1991 and 2002, we need to continue collecting data so that current conditions are better estimated and accounted for in the models and analyses.

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Degradation of Ice Wedges in Northern Alaska in Response to Recent Warmer Temperatures

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Ground observations and photogrammetric analysis indicate that there has been extensive degradation of the surfaces of ice wedges over a fifty-seven-year period on the Beaufort Coastal Plain in northern Alaska. Field observations and sampling at forty-six polygonal troughs and their intersections showed that ice wedge degradation has been relatively recent as indicated by newly drowned vegetation. We found thermokarst was widespread on a variety of terrain conditions, but most prevalent on ice-rich centers of old drained lake basins and alluvial-marine terraces, which have the greatest ice wedge development in the studied landscape. Ice wedges on these terrains typically occupy from 10% to 20% of the upper permafrost. We attributed the natural degradation to warm weather during the past decades, because disturbance of the ground surface, which could have similar impact on ice wedges, was not evident.

While ice-wedge degradation probably has been periodically occurring at low rates over the preceding centuries, it has greatly accelerated during the last several decades. Spectral classification of 1945 and 2001 aerial photography found flooding covered 13.7% of the terrestrial area (larger waterbodies excluded) in 1945 only, 3.8% in 2001 only, and 2.2% in both years. We attributed the increase in newly flooded areas (3.8% of landscape) in 2001 (a dry year) not present in 1945 (wet year) to be the result of thermokarst. The waterbody coverage provides only a minimum estimate of ice-wedge degradation, however, because ground observations indicated that many polygonal troughs over ice-wedges had indications of subsidence, yet were not sufficiently low to be covered by water. Qualitative analysis of photography from 1980 indicated that widespread ice wedge degradation had not yet occurred. The ice-wedge degradation indicates that substantial thermokarst can occur in response to decadal-scale temperature changes even in areas of cold continuous permafrost. Changes likely will increase during the next century if arctic air temperatures increase by 3–8° C as expected.

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Global Boreal Forest Responses to Climate Warming

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The Arctic Climatic Impact Assessment (ACIA) has provided the opportunity to conduct a circumpolar investigation and synthesis of climate warming and the boreal forest, including the record of recent climate change, the vulnerability of forest systems to warming, and scenarios of climate change from GCMs. A comprehensive view of the record of forest growth in relation to climate contains apparently contradictory records of opposite temperature trends in different parts of the global boreal forest. These can be explained as a result of an interconnected atmospheric circulation system with coupled regional departures that can be opposite in their temperature effects. The northernmost boreal forest also offers a unique, very long record (up to 9000 years) of very high resolution that provides important perspective when examining current climate warming effects. For example, distribution of trees (sparse stands or individuals) extended all the way to the arctic shore across the entire Russian Arctic during much of the early Holocene, as indicated by frozen wood remains in permafrost. The varied social context is another crucial factor in examining climate-warming effects on forest systems. In Iceland climate warming is producing a more favorable environment for a large-scale afforestation program; in the Nordic countries investments in forest management are at risk; and in much of Siberia, Alaska, and Canada biodiversity resources are the main focus of concern. A substantial amount of new science supports assessments of the effect of climate warming, including the Flakaliden direct warming experiment in Sweden, the IGBP Central Siberian Transect, the BOREAS project, and dendrochronological studies in Alaska. Many tree species in different parts of the northern boreal region display a positive growth response to growing season warmth. Generally these are the more humid parts of the boreal forest in eastern Canada and northern

Europe. The Central Siberia transect captures a suite of growth responses across a very large latitudinal gradient, and includes trees and sites with negative responses to warmth because of drought limitations. Strong warming in Alaska has been associated with substantial growth reductions on moisture-limited sites, which are widespread in lowlands. Scenarios of five GCMs run through the 21st century have been calibrated to empirical temperature-tree growth records. The scenarios produce climates that would be suitable for substantial increases in individual tree growth in positive-responding tree populations, such as the Taimyr Peninsula and northern Labrador. However, warmth is a critical factor in triggering events for major agents of change in boreal forests, especially fire and insect outbreaks. Warming scenarios also are associated with temperatures that, based on empirical relationships, would not be suitable for the survival of current trees on the landscape.

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Hydrological Changes in Northwest Canada

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Over the past twenty years, there has been considerable change in the snow cover, vegetation, river ice breakup, and runoff of northwest Canada. This paper will consider these changes for the Mackenzie River Delta, as well as for small streams in the forest/tundra transition zone of northwest Canada to the east of the Mackenzie Delta. The major changes to be discussed include trends toward earlier breakup of the Mackenzie River at Inuvik and earlier spring snowmelt. In addition, we will consider the potential effect of increasing shrub abundance on the hydrology of tundra areas. We will also consider our ability to model the hydrologic system in these areas under both present and future conditions. Much of this research has been carried out within the Mackenzie GEWEX Study (MAGS).

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Pan-Arctic Observations of Interannual Snowmelt Change and Application to Flood Forecast

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Global snow influences the global heat budget and has strong feedbacks with the planetary albedo and outgoing longwave radiation. Temperature change in arctic and sub-arctic regions is strongly influenced by the albedo-temperature feedback process. Hydrological and general circulation model simulations predict the largest changes in the hydrological cycle for the snow-dominated basins of mid- to high latitudes. Water cycle changes are caused in part by the greater amount of warming in these regions, but more importantly, by the role of snow in the water balance (Nijssen et al., 2001). The timing and magnitude of river discharge in the arctic drainage system are strongly related to cold season snow mass storage and subsequent snowmelt. Decadal meteorological data sets indicate an increase in the amount of precipitation in winter season, increase in spring air temperature, and adverse shifting of snowmelt onset dates (Ma et al., 2002; Lobanov et al., 2001). Long-term river-monitoring data reveal an increase in the annual discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean (Peterson et al., 2002; Yang et al., 2002). In particular, the Lena River region, a very important region for the Russian diamond mining industry, suffered catastrophic floods in recent years (1998, 1999, and 2001), and the 2001 flood was the worst in one hundred years (Nghiem and Brakenridge, 2002).

Based on a field experiment (Nghiem et al., 1999) carried out at Fort Wainwright, Alaska, we determine the relationship between Ku-band backscatter signature with the snowmelt process and snow albedo change. The experiment results are used to develop an innovative method to determine the timing of snowmelt from onset to ground exposure (complete melt) using QuikSCAT/SeaWinds satellite scatterometer data. The very wide swath of the satellite sensor provides pan-arctic observations of snowmelt two times per day. Snowmelt onset date, refreezing day, snowmelt duration, and complete melt date are obtained.

Results are used to study interannual snowmelt changes in conjunction with flooding over the Lena River region. The analysis shows a distinctive relationship between the number of snowmelt days and flood severity. Furthermore, areal percentage reduction in daily snow coverage during the snowmelt process indicates that such data can be used to predict flooding conditions. This is because changes in snow reduction or snowmelt rate can be observed, thanks to the pan-arctic coverage with the high temporal resolution of the satellite scatterometer, in advance of subsequent flood events caused by snowmelt. Images and multiple movies/animations showing the above results will be presented.

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Modeling Evidence for Recent Warming of the Arctic Soil Thermal Regime as Derived with a Finite-Difference Heat-Conduction Model

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A finite difference model for one-dimensional heat conduction with phase change is applied to investigate soil freezing and thawing processes over the arctic drainage basin. Calculations are performed on the 25 km x 25 km resolution NSIDC EASE-Grid. NCEP re-analyzed sigma-0.995 surface temperature with a topography correction, and SSM/I-derived weekly snow heights are used as forcing parameters. The importance of using an annual cycle of snow density for different snow classes is emphasized. Soil bulk density and the percentages of silt/clay and sand/gravel are from the SoilData System of the International Geosphere Biosphere Programme. In addition, we parameterize a spatially variable peat layer using specific soil bulk density and thermal conductivity. Climatological soil moisture content is from the Permafrost/Water Balance Model at the University of New Hampshire.

The model domain is divided into three layers with distinct thermal properties of frozen and thawed soil, respectively. Calculations are performed on sixty-three model nodes ranging from a thickness of 10 cm near the surface to 2 m at 30 m depth, the lower model boundary. Initial temperatures are chosen according to the grid cell's IPA permafrost classification and the model is then spun up for fifty-two years in order to obtain realistic start conditions for temperatures on all model layers.

The soil model is run for the twenty-two-year period 1980 through 2001 with a daily time step. We present results for soil temperature at different depths for the whole arctic terrestrial drainage, and for active layer depth in permafrost regions. Simulated thaw depths are compared to late-summer measurements made at sixty-six CALM field sites within the continuous and discontinuous permafrost regions. A remaining RMS-error between modeled and measured values is attributed mainly to scale discrepancies (100 m x 100 m vs. 25 km x 25 km) based on differences in the fields of air temperature, snow height, and soil bulk density. Also, annual soil temperature cycles at different depths compare fairly well with measurements in Alaska and Siberia. Trends in active-layer depth and in soil temperatures at different depths are set into relationship with trends in air temperature and snow forcing data, and reveal a clear warming trend of the arctic soil thermal regime over the past twenty plus years. These trends are positive for all permafrost regions and largest for the region of continuous permafrost with a warming of about 0.03 K/yr at the surface. Seasonal soil surface temperature trends as high as 0.05 K/yr are found for spring and for fall, but winter and summer trends are lower with about 0.02 K/yr. The warming rate for continuous permafrost regions has increased to about 0.15 K/yr for the last eight years of the time series (1994–2001).

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Measured Climate-Induced Volume Changes of Three Glaciers and Current Glacier-Climate Response Prediction

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Two small but hydrologically significant shifts in climate have affected the rates of glacier volume change at the three U.S. Geological Survey Benchmark glaciers. Rate changes are detected as inflections in the cumulative conventional and reference-surface mass-balances of Wolverine and Gulkana Glaciers in Alaska and South Cascade Glacier in Washington. All mass-balance trends and inflection points are strongly correlated with the 1976–77 and 1989 interdecadal climate-regime shifts that are recognized in several climate indices for the North Pacific and the National Center for Environmental Prediction (NCEP) re-analysis data. Wolverine Glacier is a south-facing valley glacier on the Kenai Peninsula in south-central Alaska. Gulkana Glacier is a south-facing branched valley glacier on the southern flank of the Alaska Range in interior Alaska, about 350 kilometers northeast of Wolverine Glacier. South Cascade Glacier is in the North Cascade Mountains of northern Washington. The cumulative mass balances are robust and have recently been corroborated by geodetic determinations of glacier volume change. Furthermore, the four-decade length of record is unique for the western hemisphere. Balance trends at South Cascade Glacier in Washington are generally in the opposite sense compared with Wolverine Glacier in Alaska; NCEP correlation of winter balance with local winter temperatures is positive at 0.59 for Wolverine and –0.64 for South Cascade Glacier. At Wolverine Glacier, the negative trend of cumulative mass balances, since measurements began in 1965, was replaced by a growth trend (positive mass balances) during the late 1970s and 1980s. The positive mass-balance trend was driven by increased precipitation during the 1976-77 to 1989 period. At Gulkana Glacier, the cumulative mass-balance trend has been negative throughout its measurement history, but with rate-change inflection points that coincide with the interdecadal climate-regime shifts in the North Pacific indices. At South Cascade Glacier, the mass-loss trend, observed since measurements began in 1953, was replaced by a positive trend between 1970 and 1976, which then became strongly and continuously negative until 1997 when the rate of loss generally decreased. Since 1989, the trends of the glaciers in Alaska have also been strongly negative. These loss rates are the highest rates in the entire record. The strongly negative trends during the 1990s agree with climate studies that suggest that the period since the 1989 regime shift has been unusual.

Volume response time and reference surface balance are the current suggested methods for analyzing the response of glaciers to climate. Volume response times are relatively simple to determine and can be used to evaluate the temporal, areal, and volumetric affects of a climate change. However, the quasi-decadal period between the recent climate-regime shifts is several times less than the theoretical volume readjustment response times for the benchmark glaciers. If hydrologically significant climate shifts recur at quasi-decadal intervals and if most glaciers' volume-response times are several times longer (true for all but a few small, steep glaciers), most medium and large glaciers are responding to the current climate and a fading series of regime shifts which, themselves, vary in magnitude. This confused history of driver trends prevent conventional balances from being simply correlated with climate. Reference-surface balances remove the dynamic response of glaciers from the balance trend by holding the surface area distribution constant. This effectively makes the reference surface balances directly correlated with the current climatic forcing. The challenging problem of predicting how a glacier will respond to real changes in climate may require a combination of the volume response time and reference surface mass balances applied to a long time-series of measured values that contain hydrologically significant variations.

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Potential Factors Contributing to Long-term Increases in Discharge from Large Eurasian Drainage Basins: A Preliminary Analysis

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Recent analysis by Peterson et al. (2002) documented a statistically significant upward trend in long-term discharge from a major portion of the Eurasian land mass represented by major rivers draining into the Arctic Ocean. The increase totaled 7% from 1936–99. If sustained, these modified land-to-ocean fluxes hold the possibility for modifying global ocean circulation though impacts on thermohaline circulation. The sources of this rise in river flow are unknown.

A preliminary assessment of the major contributing factors is offered. The potential mechanisms include both physical and biologically mediated processes. Physical climate-mediated changes include alteration of thermal loads and the cycling of water. Potential changes are associated with precipitation, evapotranspiration, net convergence, snow cover and water content, loss of glaciers, and changes in permafrost active layer. Landscape changes in lake and wetland distribution, natural and human-induced land use, and nutrient biogeochemistry also could have impacts on continental-scale water budgets. Water resource management, in the form of runoff distortion and consumptive use, may also be implicated. In this context, the impact of uncertainties in runoff caused by observing network deterioration and errors in discharge measurements across the region are assessed.

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Detecting Arctic Climate Change Using Köppen Climate Classification

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Ecological impacts of the recent warming trend in the Arctic are already noted as a decrease in tundra area with replacement of ground cover by shrubs, and changes in the tree line. The potential impact of vegetation changes to feedbacks on the atmospheric climate system is enormous because of the large land area impacted and the multiyear memory of the vegetation cover. Satellite NDVI estimates beginning in 1981, and the Köppen climate classification are used to relate surface types to monthly mean air temperatures. These temperatures from the NCEP/NCAR reanalysis and CRU analysis then serve as proxy for vegetation cover over the century.

The results suggest a decrease in the area of tundra group from the mid 1970s to the present, which is negatively correlated with the trend of the NDVI data in the arctic region. The decreases are largest in northwest Canada and eastern and coastal Siberia. A similar decreasing trend was found at the earlier 1900s, but with smoother slope. Thus tundra area tracks arctic change with a weak downward trend for the first forty years of the 20th century, followed by two increases during the 1940s and early 1960s, and then a more rapid decrease in the past twenty years. Because of the way each climate group is defined, we interpret the results as that the warming in the 1920–40 period is limited to the southern boundary of the arctic region, whereas the warming since 1980 is pan-arctic-wide, and happened during both the spring and summer seasons. The calculated tundra area minimum in 1998, from both analyses, indicates that the warming in the 1990s is the strongest in the century, and may have inevitable affects in the Arctic.

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Streamflow Changes over the Large Siberian Watersheds: Natural Variation vs. Human Impact

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Observational records show significant climate change in the high-latitude regions over the past several decades. Hydrologic response of the large northern watersheds to climate change and variation is one of the key issues in understanding atmosphere-land interactions in the northern regions. Examination and documentation of changes in the major northern rivers are also important to studies of global change, regional water resources, and distribution of ecosystems. In order to describe the seasonal regime of river streamflow, and to document significant streamflow changes induced by human activities (particularly reservoirs) and by natural variations/changes, this study analyzes the long-term monthly streamflow records over the past forty to fifty years for the large Siberian watersheds, such as the Lena, Yenisei, and Ob rivers. The results show significant changes in streamflow characteristics. These include amount and timing of snowmelt runoff, summer season discharge, and increases in winter discharge over most of the watersheds. These changes may indicate a hydrologic regime shift due to recent climate warming over the northern regions. They may also be related to changes in permafrost conditions and influenced by human activities.

Detail analyses of Lena basin monthly streamflow data show that the upper streams of the watershed, without much human impact, experience a runoff increase in winter, spring, and (particularly) summer seasons, and a discharge decrease in fall season. These changes in seasonal streamflow characteristics indicate a hydrologic regime shift toward early snowmelt and higher summer streamflow, perhaps due to regional climate warming and permafrost degradation in the southern parts of Siberia. The results also demonstrate that reservoir regulations have significantly altered the monthly discharge regime in the lower parts of the Lena River basin. Because of a large dam on the west Lena River, summer (high) flows at the outlet of the Vilui Valley have been reduced by up to 55% and winter (low) flows have been increased by up to thirty times. These alterations, plus streamflow changes in the upper Lena regions, lead to strong upward trends (up to 90%) in monthly discharge at the basin outlet during the low flow months and weak increases (5–10%) in the high flow season. Monthly flow records at the basin outlet have been reconstructed by a regression method to reduce reservoir impacts. Trend analyses and comparisons between the observed and reconstructed monthly flows show that, because of reservoir regulations, discharge records observed at the Lena basin outlet do not always represent natural changes and variations. They tend to underestimate the natural runoff trends in summer and overestimate the trends in both winter and fall seasons. Therefore, cold season discharge increases at the Lena basin outlet are not all natural-caused, but the combined effect of reservoir regulation and natural runoff changes in the unregulated upper sub-basins. This study clearly illustrates the importance of human activities in regional and global environment changes. More efforts are needed to examine human impacts in other large high-latitude watersheds.

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Permafrost Thawing and Hydrologic Response over the Russian Arctic Drainage Basin

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Recent studies indicate that runoff over the Siberian arctic drainage basin in the past several decades has increased substantially. The source of water causing the runoff increase is unknown. In this study, we hypothesize that changes in the active layer and permafrost dynamics play a key role in the recent changes in the arctic hydrological regime. We document 1) permafrost and ground ice distribution; 2) changes in permafrost temperature, active layer thickness, and length of thaw season over the past few decades, and 3) their impact on the hydrologic cycle over three Siberian river basins: the Ob, the Yenisey, and the Lena.

Permafrost underlies approximately 4% to 10% of the total area of the Ob basin, the least among the three river basins, 36% to 55% in the Yenisey basin, and 78% to 93% in the Lena basin. Consequently, total volume of the excess ground ice varies from approximately 302 to 854 km^3 in the Ob, 1,699 to 2,462 km^3 in the Yenisey, and 3,523 to 4,227 km^3 in the Lena basin. Based on ground-based measurements, mean annual soil temperature at 40 cm depth has increased about 1.3^o C in the Ob, 0.8^o C in the Yenisey, and 1.6^o C in the Lena river basin for the period from 1930 through 1990. The increase is more pronounced from the mid-1960s to 1990. An increase in the near-surface soil temperature leads to lateral thawing of permafrost and thickening of the active layer.

Long-term soil temperature measurements indicate that permafrost has been degrading during the past several decades. Active layer thickness has increased about 15 cm from the mid-1960s to the mid-1980s over the Lena river basin. Thawing index has increased substantially over all three river basins from the 1950s to 1990s, implying that the increase in active layer thickness has been a widespread phenomenon over the Russian arctic drainage basin during the past few decades. Changes in active layer thickness of 15 cm are runoff equivalent of about 0.9 to 2.4 mm in the Ob, about 7.8 to 11.3 mm in the Yenisey, and about 15.3 to 19.4 mm in the Lena. Overall, changes in permafrost conditions in the Ob basin have a minimum impact on runoff. Lateral thawing of permafrost and thickening of the active layer may account for the significant increase in runoff over the Yenisey River basin. Melting of the excess ground ice through thickening of the active layer might be the major source of water to the runoff in the Lena river basin. The onset of the thawing season started earlier in spring and the last date of thaw season became later in the autumn. As a result, the length of thaw season increased by fifteen to twenty-five days. An increase in the length of thaw season and thickening of the active layer delay the freeze-up date of the active layer. Late freeze-up of the active layer partly explains the increased runoff during winter months.

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Simulated Water and Energy Fluxes of the Pan-Arctic Land Region

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The first objective of the terrestrial component of SEARCH is to assess changes over the last few decades in the hydro-climatology of the pan-arctic drainage basin. Variables of interest include freshwater discharge to the Arctic Ocean, snow cover extent, snow water equivalent (SWE), and permafrost extent and depth. Due to the sparseness of discharge measurements and the variability between catchments in the pan-arctic drainage basin, hydrologic modeling must play a strong role in estimations of the spatial and temporal (seasonal and inter-annual) variability of land surface hydrologic states and fluxes.

We report a twenty-year (1979–98) run of the Variable Infiltration Capacity (VIC) macroscale hydrologic model, over the pan-arctic land domain. VIC is a semi-distributed grid-based model that parameterizes the processes occurring at the land-atmosphere interface. Recent cold-region developments in VIC include: improvements to the frozen soils algorithm to simulate permafrost; development of an algorithm to represent the hydrologic effects of lakes and wetlands; and development of an algorithm that estimates the redistribution and sublimation of blowing snow. For the twenty-year simulation period, VIC was applied over a 50 km by 50 km Lambert Equal-Area (EASE) grid projection. We examine inter-annual variability in pan-arctic water and energy balances, as well as various partitions thereof at continental and major river basin scales. We also compare VIC prognostic variables with observations and NCEP/NCAR reanalysis where and when possible.

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Late-Holocene Lake-Level Variation in West Greenland

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Student Poster

Situated between the North Atlantic and the Greenland ice sheet, the thousands of lakes in the Kangerlussuaq area of West Greenland (67°N) present excellent targets for paleoclimate studies. Paleoshorelines surrounding multiple closed-basin lakes in this area record fluctuations in lake level since deglaciation. Shorelines along two of these lakes, Hundeso and Lake E, were surveyed and trenched to reconstruct the history of lake-level change. The stratigraphies of the trenches were described, and a chronology has been developed using radiocarbon dating of organic material. Preliminary results indicate a highly variable hydrologic regime throughout the late Holocene.

Hundeso had high-stand lake levels ~810 and 1950 ^{14}C yr. B.P., reaching elevations 4–5 meters above present lake level. Topographic data show that at these times Hundeso was joined with several neighboring lakes to form a “mega lake” that covered over 520 ha. Lake E also experienced high stands at the same time (830 and 1920 ^{14}C yr. B.P.), with lake levels 1–2 meters above present.

This study presents the first direct evidence of Holocene lake-level variability in this region, and can be used to constrain the interpretation of other paleoclimate proxies in cores from regional lakes. Our data suggest substantial hydrologic variation during the past 2,000 years, including the highest lake stands since the lakes were formed ~8,000 years ago.

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Rapid Wastage of Alaska Glaciers: The Search for Climatic Causes

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According to our airborne laser altimetry measurements, the volume change of Alaska's glaciers was -46 km^3/year between the mid-1950s and the mid-1990s, and -88 km^3/year between the mid-1990s and 2000–2001. Here we relate these changes in glacier mass to climate patterns in Alaska during the past fifty years. Climate station data show that Alaska's annual temperatures have increased by an average of 1.5° C, with the greatest increases occurring in the spring and winter months. Surface observations suggest total precipitation has increased along coastal regions, although more precipitation is falling as rain instead of snow in these areas. Upper air data show increases in mean freezing heights over many regions of Alaska, indicating precipitation is also falling more often as rain at higher elevations.

We use a degree-day mass balance model to relate changes in temperature and precipitation to the mass balances of Gulkana and Wolverine Glaciers, located in interior and coastal regions of Alaska, respectively. Simulations predict that the observed change in summer temperature (+0.8° C) at Gulkana Glacier caused a change in glacier-wide balance of -0.30 m/year, similar to -0.34 m/year measured by altimetry. The model predicted that observed changes in summer temperature (+0.7° C) and precipitation (-3.5 mm/year) at Wolverine Glacier changed the glacier-wide balance by -0.23 m/year, about half of the observed value of -0.51 m/year. The modeled balance at Wolverine Glacier matched the observations when winter snowfall was reduced by an additional 25%, suggesting observed precipitation changes underestimated actual changes. Additional simulations showed that the mass balance of Gulkana Glacier was more sensitive to late summer season rather than early summer season temperature increases. At Wolverine Glacier, the change in mass balance was almost independent of the timing of summer temperature increase.

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Changes in River Runoff over the East-Siberian Sea Basin

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The main rivers flowing to the East-Siberian Sea (ESS) are the Kolyma, Indigirka, and Alazeya Rivers. Altogether these rivers bring 151 km^3 of fresh water per year to the East-Siberian Sea. A sparse network of hydrological stations is mainly located in the upper and middle basins of the Indigirka and Kolyma Rivers. The interfluves and the eastern part of the ESS basin are practically ignored in the runoff observations.

The Kolyma River, in the upper and middle reach, drains mainly mountain terrain, flowing along the Kolyma lowland in downstream. The Indigirka River's watershed covers both mountainous and lowland territories, whereas the Alazeya River primarily drains the near-shore lowland (Kolyma Lowland) containing plenty of thermokarst lakes and swamps. It causes the significant difference in their water regimes. The Kolyma River is characterized by pronounced spring-summer (May-June) flooding with the summer-autumn short-term floods, whereas at the Alazeya and Indigirka outlet stations, the flooding wave is more flat and smoothly passes the period of summer-autumn floods. The autumn runoff (September-October) significantly increased in recent decades at the Indigirka and Alazeya Rivers. The average change in autumn runoff at the Voronzovo station (Indigirka River outlet station) comprises 61% from 1937 to 1994. However, analysis of long-term precipitation in September along the Indigirka River shows a decreasing trend in recent decades (1973–1993). In order to understand the reasons for autumn runoff increase, the roles of aufeis impact, thermokarst lakes, and permafrost dynamics have been analyzed.

The runoff increase during the winter season is strongly pronounced at middle and low reach of the Kolyma River from 1980. This increase is associated with the dam and Kolymskoe reservoir construction at the Sinegorye station section. The Indigirka and Alazeya Rivers don't reflect any significant change in the winter discharge in recent decades implying the strong winter runoff increase is due to dam establishment.

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The Development of Long-term and Spatially Representative Permafrost Databases

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Outputs from hemispheric and regional models of permafrost distribution provide both temporal and spatial values of ground temperature and active-layer thickness. Field validation of these models depends on availability of past and current empirical data. Maps and models depicting current and future change in permafrost boundaries depend on these field observations over long time intervals. Over the past several decades there has been a concerted effort to organize permafrost data for existing sites under the Global Geocryological Database (GGD). More recently, several networks have been identified for active-layer thickness and borehole temperatures under the Global Terrestrial Network for Permafrost (GTN-P). The Circumpolar Active Layer Monitoring (CALM) program, a network under the GTN-P, currently reports data from approximately 125 sites, obtained by personnel from fourteen participating countries. The borehole network identified approximately 350 sites in thirteen countries from which data are or have been obtained. The GTN-P is one of the WMO Global Climate Observing System (GCOS) networks and is coordinated by the twenty-four-member International Permafrost Association and its several committees.

In the U.S. an interagency committee chaired by NOAA/NESDIS prepares GCOS status reports. In the most recent WMO/GCOS adequacy report required by the United Nations Framework Convention on Climate Change (UNFCCC) the following findings were stated: "New temperature boreholes and in situ observations of active layer need to be established in both hemispheres by the Parties at sites identified by the Permafrost Network with the observations provided to Network's international data centre." http://www.wmo.ch/web/gcos/gcoshome.html

Future GTN-P activities will address issues related to spatial representation of sites and the design and establishment of additional long-term permafrost observatories such as now exist in northern Alaska, Canada, and in Europe under the European Union's project Permafrost and Climate in Europe (PACE). An observational campaign within the IPA/GTN-P is proposed as a contribution to the International Polar Year.

A third IPA-coordinated network under the Arctic Coastal Dynamics (ACD) project is concerned with long-term observations of coastal erosion. Under this program, recently identified as an IGBP Land Ocean Interaction in the Coastal Zone (LOICZ) project, a series of twenty or more key sites located around the circum-arctic coastline provide in situ data for rates of coastal erosion. An annual workshop funded by IASC provides the venue for a number of synthesis activities http://www.awi-potsdam.de/www-pot/geo/acd.html.

Observations and international coordination of the CALM network are supported through NSF grants http://www.geography.uc.edu/CALM . The Geological Survey of Canada maintains the inventory of borehole sites, and the U.S. Geological Survey provides input to the U.S. GCOS process. GTN-P data are available online and on CDs produced at the National Snow and Ice Data Center with support from the International Arctic Research Center.

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The Chemical Composition of Snow Across Northwestern Alaska and the Potential Ramifications of a Warming Arctic

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Continued warming of the Arctic and the subsequent thinning and loss of Arctic Ocean sea ice will affect the deposition of aerosol contaminants in northern Alaska. In order to better understand the spatial and temporal aspects of current chemical deposition pathways we sampled three layers of snow at sixteen sites along a 1,200 km transect from Nome to Barrow. Samples were analyzed for major element concentrations, oxygen and hydrogen isotopes, specific conductance, and pH. Samples from five of the sites were also analyzed for trace element concentrations.

Pb, Cd, SO_4^{2-} and non-sea salt SO_4^{2-} concentrations were significantly higher in layers deposited later in the winter than those deposited in early winter. This is consistent with the seasonal increase in atmospheric aerosol loading (arctic haze) that develops as the arctic polar front expands southward in March and April. Haze contaminant concentrations in the snow pack were as high south of the Brooks Range as they were to the north, suggesting the Brooks Range is not an effective orographic barrier to aerosol transport. Elevated concentrations of Hg, Na and Cl were measured near the Arctic Ocean coast but not near the Bering Sea coast.

In an attempt to explain this asymmetrical spatial deposition pattern we introduce the idea of the "effective distance from the coast," as inferred from prevailing wind directions and storm tracks. This distance is critical in governing whether halogen emissions from the ocean are available for photochemical reactions that result in mercury deposition to the snow pack. We speculate how current deposition patterns would change under a warmer arctic climate.

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Atmosphere-Ocean Teleconnections and Alaskan Forest Fires

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The boreal forest is a huge biome that contains large stores of carbon. Most aspects of ecosystem dynamics in the boreal forest are controlled by wild fires, but the drivers of the fire regime are poorly understood. Some researchers suggest that the fire regime is modulated by the vegetation in the course of decade-scale cycles of secondary succession and at millennial time scales by changes in tree species abundances. Others think that regional climate is the dominant driver of the fire regime. Here we use a multiple linear regression model to quantify relationships between climatic variables and the annual area burned in Alaska over the past fifty years. The seasonality of the circulation-fire linkage is addressed through a systematic evaluation of the East Pacific teleconnection field keyed to an annual fire index. The impacts of ocean-atmosphere interactions are examined through the use of equatorial sea surface temperatures as explanatory variables in the regression model. Six explanatory variables and an interaction term collectively explain over 80% of the variability in the natural logarithm of the number of hectares burned annually in Alaska from A.D. 1952 to 2002. Results reveal that tropical sea surface temperatures and the East Pacific teleconnection (EPT) exert an influence on short-term climate and weather in Alaska. Strong positive phases of the EPT are associated with upper airflow that is more meridional in nature. This meridional flow is conducive to the development of mid-troposphere anomalies that affect short-term weather and fire behavior. Negative phases of the EPT are associated with strengthened westerlies in the eastern North Pacific as a consequence of a more zonal upper airflow. The shift in sign of the teleconnection over a period of several months exerts a significant signal on both temperature and precipitation during the spring and summer in Interior Alaska, while SST anomalies exert an influence on snow pack development through

influences on October and November precipitation. These results suggest that climate is an important driver of the fire regime in the boreal forest; however, there is more to fire regime than the number of hectares burned. Lacustrine records of charcoal and observations on the interactions between fuel type and fire behavior all suggest that there are important biological feedbacks involved. We are currently exploring the rich behavior that results when climate drivers are linked to vegetation dynamics in a landscape-scale model of ecosystem dynamics.

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International Polar Year 2007-2008

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The year 2007–08 will mark the 125th anniversary of the First International Polar Year (1882–33), the 75th anniversary of the Second Polar Year (1932–33), and the 50th anniversary of the International Geophysical Year (1957–58). The IPYs and IGY were important initiatives that resulted in significant new insights into global processes and led to decades of invaluable polar research. But in spite of the substantial effort in polar exploration and research over the years, both by individual nations and through international programs, the relative inaccessibility and challenging environment have left these regions less explored and studied than other key regions of the planet. Earth system processes in the polar region remain significantly less understood relative to our understanding of processes in other, more accessible regions.

Planning is underway to hold an International Polar Year (IPY) in 2007–08. It is envisioned as an intense program of internationally coordinated polar observations, exploration, and analysis, with strong education and outreach components. To be successful, IPY should be visionary and more than a continuation of present efforts (although current and planned efforts and enabling technologies should be part of what is done). It must address both the Arctic and Antarctic, and look for linkages between the regions. It must be multi-disciplinary, including study of human dimensions, and truly international. Ideally, IPY will provide both specific short-term outcomes and lay a foundation for longer-term commitments. If done well, IPY could attract and develop a new generation of polar scientists.

The International Council on Science (ICSU) has endorsed the IPY concept and has encouraged nations to determine their priorities. An ICSU Planning Group is preparing a draft science plan for distribution in February 2004. Thus, this is an important time for the science community to articulate its interests. This presentation will outline current ideas for the next IPY, with a specific emphasis on projects related to the land. The objective is to inform participants of current plans and gather input on other ideas and programs that could be integrated into the next IPY.

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Observation of Snowmelt Progression in Northern Alaska with Spaceborne Active Microwave

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The transition from snow cover to snow free conditions for the arctic land surface is a significant event in the arctic hydrologic cycle. Acquisitions from active satellite microwave sensors such as scatterometers can be used to observe the spatial and temporal progression of snowmelt processes. NASA Scatterometer (NSCAT) data acquired during the 1997 melt season are used to classify northern Alaska conditions as dry snow, wet snow, snow free, and snow which is experiencing melt/freeze transitions. The NSCAT data have been temporally averaged over six-day intervals to insure continuous spatial coverage. The classification algorithm uses the mean backscatter as well as the standard deviation of the backscatter for each interval. Classification thresholds were determined based on meteorological station data and ground-based snow water equivalent (SWE) measurements. The spatial progression of the classified snowpack conditions correspond with NCEP/NCAR reanalysis air temperature data. Maps of the timing of snowmelt onset, snow-free ground and the number of melt days are presented.

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Direct Observation of Winter Sublimation and Its Effects on the Arctic Climate

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Snow sublimation is a key factor affecting arctic climate and hydrology, but the mechanism has been poorly understood, especially winter processes. Improved accuracy in representing snow sublimation is crucial to revealing arctic climate and hydrology and accurately modeling arctic climate.

Since Spring 1999, we have been measuring fluxes and micrometeorology at Barrow, Alaska. We detected large episodes of sensible, latent heats and CO_2 fluxes from the tundra surface to the atmosphere during blizzards in mid-winter, which is the first direct measurement of winter sublimation. Winter sublimation occurred when wind speed was over 6 m/s with temperatures below -15° C, and the fluxes increased with cubic of wind speed. The maximal latent heat flux reached 320 Wm^{-2} and the total released energy was 540 Wm^{-2}, respectively. The upward fluxes continued over forty-eight hours and the sensible and latent heat fluxes reached 12 and 16 MJ m^{-2}, respectively. The latent heat flux was equivalent to 5.7 mm of water depth of snow sublimation. The released energy through the observed sublimation amounted to 82 MJ m^{-2} (averages 5.3 W) between November 2000 and March 2001, which allows to increase arctic temperature around 0.15° C.

Therefore, the energy input to the arctic plain (ice surfaces of land and sea) through winter sublimation is important to climate and its modeling in the Arctic.

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Lightweight Shallow Ice Coring and Borehole Logging Can Provide Decadal- to Millenial-Scale Indicators of Climate Change Around the Arctic Basin

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Student Poster

Data from coring and borehole logging in ice caps (large or small) can add significant value to climate research programs by providing a longer time-scale view of important climatic indicators. While the length of the instrumental record is limited to about one hundred years, the length of the paleoclimate record from ice cores is limited only by the depth and relative accumulation rate of the ice-core site. For example, shallow (250 m) coring programs on the Devon Island Ice Cap have recovered annual- to decadal-resolution climate records more than 5,000 years long, while recent NASA-funded shallow and intermediate coring on the Greenland Ice Sheet has provided detailed spatial records of net accumulation and glaciochemistry over recent decades to centuries.

A new generation of lightweight drills for shallow coring allows a shallow (~10–50 m) ice core to be drilled, logged, and packed in a single day, and intermediate-depth cores (50–200 m) to be taken in a week. New continuous-melter analysis techniques allow rapid, high-resolution, precisely-coregistered multiparameter chemical analysis. The hole "left over" from the coring effort can be logged with various tools to further our understanding of past climate.

In particular, Borehole Optical Stratigraphy (BOS) is a technique for rapidly logging optical properties in ice which are directly linked to climate indicators. Using BOS, we can identify annual layers and melt horizons in an ice cap, measure vertical motion in the ice, and potentially determine a density and grain-size profile. This information can be related to useful quantities for paleoclimate modeling such as temperature and precipitation. Chemical analyses of the extracted core can also provide paleoclimate time series, and together, all these techniques can provide a comprehensive picture of past climates, including both averages and extreme events.

A pan-arctic coring and logging program could efficiently extract paleoclimate records from many ice caps around the arctic basin, allowing analysis of the spatial patterns of paleoclimate. Within a single icecap, multiple coring sites can accurately characterize local climate zones, and gradients related to regional weather patterns and storm tracks, in order to place that ice cap in the context of the Arctic as a whole.

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In Search of the Younger Dryas at Elikchan Lake, Northeast Siberia

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Student Poster

The Younger Dryas (YD) was a late Pleistocene climatic oscillation that occurred approximately 11,000–10,000 ^{14}C yr B.P. (13,000–11,500 cal yr B.P.), after a millennium of post-glacial climate amelioration. Characterized by dramatic and abrupt climatic cooling over much of the world, the YD has generated a great deal of scientific interest, particularly due to its extremely rapid termination. The global distribution of the YD signal has been the focus of much attention, as an understanding of global geographic extent is essential for determining the mechanisms and causes of paleoclimatic change. Such an understanding is extremely valuable in the face of future climate change, as climatic patterns and ecosystem responses seen in the past can help predict how different components of the climate system might react in the future.

Although the YD has been referred to as a global event, analysis of paleo-data indicates that not all high latitudes experienced a climatic response to the YD. In Beringia, the area encompassing northeast Siberia, Alaska, and northwest Canada, the YD signal is complex. Far western Beringia and southern areas of eastern Beringia appear to register dramatic cooling during the YD; northern and interior areas of eastern Beringia register a mixed signal; and most of western Beringia shows uninterrupted warming into the Holocene, with the exception of Wrangel Island where its appears to have been warmer and wetter than present during the YD. Importantly, however, many of the studies conducted in western Beringia were not of high enough resolution to have recorded the brief and abrupt climatic event of the YD, or they did not have well-constrained dating control. To address this issue, this study uses a multi-proxy, high resolution analysis to identify any YD signal in a sediment core taken from Elikchan Lake, northeast Siberia. The sediment core was analyzed for sediment magnetic susceptibility, grain size, fossil pollen assemblage, organic carbon content, and biogenic silica content at approximately one-hundred-year intervals. Interestingly, the data show a strong signal marking the glacial to interglacial transition but they do not reflect any abrupt changes that would be expected for a YD event.

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Consideration of Permafrost Thaw as a Significant Contributor to Increasing Eurasian Arctic River Discharge

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Examination of long-term discharge records has shown that the combined discharge from the six largest Eurasian arctic rivers (Yenisey, Lena, Ob, Pechora, Severnaya Dvina, Kolyma) increased 7% from 1936–99. Thus, these six rivers now contribute on average 128 km^3/y more freshwater to the Arctic Ocean now than they did when discharge monitoring began in the 1930s. Projection of arctic river discharge trends into the future, including possible implications for ocean circulation and climate, depend in large part on the causes of the observed increase. Possible explanations for the observed discharge trend include increased precipitation due to global warming, changes in disturbance regimes involving fires and forestry, dam construction and operation, and thawing of permafrost.

Here we focus on the potential role of permafrost thaw as a significant contributor to the observed trend. If permafrost was making a significant contribution to the observed increase in discharge in these large Eurasian arctic rivers, we might expect that watersheds with the most permafrost would show the biggest increase in runoff. No such pattern is apparent. In fact, the river with the most permafrost in its watershed (Kolyma River, 100% permafrost coverage) showed the least change in runoff, whereas the Severnaya Dvina River (with no permafrost in its watershed) had one of the largest increases. Furthermore, increases in active-layer depth that would be needed to support the observed increase in discharge (assuming all the thawed water was available for discharge—an unlikely scenario) are large (several meters over the entire 4.3 x 106 km^2 area of permafrost in these six watersheds), and much greater than has been observed. Therefore, we conclude that permafrost thaw is not a significant contributor to the observed long-term increase in Eurasian arctic river discharge.

Carbon Storage and the Role of Cryoturbation in the High Arctic: Thule, Greenland

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Student Poster

Cryoturbation, a suite of physical processes that mix, heave, and thrust material, is common to most soils of the high Arctic. This process is likely to influence carbon cycling by burying carbon to depth and exposing previously buried carbon. Cryoturbation is controlled largely by three factors: the frequency and rate of freeze-thaw cycles, soil moisture, and soil texture. The first two factors may be altered due to anticipated increased warming and precipitation, which is predicted to be drastic in the high Arctic. Carbon storage in the high Arctic is largely unknown, and current estimates are based primarily on the upper 20–25 cm of soil (Bliss and Matveyeva, 1992). Our research, based on subsurface exposures and patterned ground features, will provide a more complete assessment of the amount of carbon stored at depth in the high Arctic and the role of cryoturbation in soil carbon accumulation.

Fieldwork began in summer of 2003 at the Thule Air Base in northwest Greenland (76°N, 68°W) and sampling was conducted in three vegetation community types: polar desert, polar semi-desert, and fens. Soil samples will be analyzed for particle size distribution and carbon content, and a selection of samples ^{14}C dated to estimate long-term soil carbon turnover rates. Future sampling will be conducted on silicate- and carbonate-dominated parent material along elevation-moisture transects of the three community types to capture carbon variations that may occur in lithology, topography, and community.

This research is a component of a multidisciplinary, multi-university National Science Foundation (NSF) biocomplexity project (#0221606) studying the interactions of physical, chemical, and biological processes in controlling carbon cycling in the high Arctic. Impacts of our combined results will provide better estimates of carbon storage and its potential release or sequestration in high-arctic soils.

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Extreme Runoff Events in Arctic Alaska

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Past history has shown that a warmer climate produced greater precipitation (greater turnover in atmospheric moisture) in the high latitudes. This increased precipitation could fall as rain or snow. Obviously, greater snowfall was required to produce the ice sheets. Presently, only one-third of the annual precipitation falls as snow in northern Alaska. However, every spring during ablation a significant runoff event occurs, often the largest event of the year. In July 1999 and August 2002, two large summer precipitation events occurred that produced summer floods four times greater than the maximum snowmelt floods previously measured.

It has been documented that the Arctic is getting warmer, primarily in the winter. It has not been documented that there has been an increase in precipitation. Existing precipitation data in the Arctic is both limited and of questionable quality. Snowmelt runoff magnitudes for a given watershed are a function of the snow water equivalent and the climate (sustained or intermittent melt). Rainfall precipitation magnitudes are a function of atmospheric conditions and how much moisture can be held in an air mass. With a warmer environment, will we see more extreme precipitation events and are the two large floods observed in 1999 and 2002 an indication of increasing precipitation?

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Arctic Ungulates in a Changing Climate

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Arctic ungulates are faced with the challenges of adapting to cascading affects on their ecology of the changing climate and associated influences of human activities on their habitats. Adaptability has characterized caribou, reindeer, and muskoxen in the past, else they would not be so successful throughout much of the Arctic today. However, the influences of a changing climate affect the arctic vegetation that supports these herbivores. In summer, precipitation, soil moisture, heat input, and solar insolation ultimately affect plant productivity, and less directly, other components of arctic ecosystems. Forage quality is affected by changes in solar insolation via cloud cover and UV-B radiation. In winter, changing climate affects availability of forage to arctic ungulates through its influence on snow depth and density, icing events, and timing of onset and melt-off of snow cover.

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R-ArcticNet v3.0 - A New and Improved River Discharge Database to Meet the Needs of High-Latitude Geoscientific Research

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We report on a significant update to the R-ArcticNet database representing river discharge covering the entire pan-arctic region. R-ArcticNET v2 was released in 1999 with over 3,500 gauges and 90 thousand station years covering monthly observations up to the late 1980s (Russia) and the early 1990s (Canada and USA). We are now in the process of finalizing R-ArcticNET v3. This database has more than 5,000 stations and 128 thousand station years of data. Time series were expanded for many gauges up to 1999.

The database also documents the huge rise and subsequent decline of hydrological monitoring activities throughout the entire pan-Arctic during the second half of the 20th century. This observed decline in monitoring of the hydrological cycle parallels in many ways the overall downward trends in river monitoring around the globe. In many cases, the closure of gauges represents a large reduction in total monitored land area.

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The Spatio-Temporal Pattern of Peatland Development in the Western Siberian Lowlands and the Potential Impact of Northern Peatlands on the Global Carbon Cycle

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The largest northern peatland complex in the world is found in the Western Siberian Lowlands (WSL) and covers some 600,000 km^2. The development of high-latitude peatlands was an important component in postglacial landscape development and significantly impacted the hydrology, flora, fauna, and human occupants of the sub-arctic. In addition, peatland development influenced atmospheric carbon concentrations through the opposing impacts of sequestering carbon and generating methane. Understanding the temporal and spatial history of high-latitude peatlands is critical to understanding the dynamics of the global carbon cycle.

We radiocarbon dated the basal peats from eighty-seven cores taken from 60° N to the arctic coastline in the WSL. Combined with existing Russian radiocarbon dates this provided over one hundred age estimates for the initial formation of peatlands in the WSL. In order to develop a circumpolar history of peatland initiation we collated published basal radiocarbon dates from subarctic peatlands in North America and Eurasia. The results indicate that subarctic peatland development commenced in the early Holocene—by around 11,500-11,000 cal yr B.P. in the WSL and some ice-free areas of North America. This period of initial peatland development also coincides with the development of northern boreal forest in Siberia.

Peatland initiation in the WSL does not show a strong latitudinal or longitudinal pattern. In contrast, the southern fringes of the current peatland zone in central Canada mainly developed in the late Holocene. Carbon analysis of the WSL cores and the GIS based analysis of our data and older Russian peat depth data provide a new peat carbon pool estimate of 70.2 Pg C for the WSL. This value is highly conservative because like previous investigators we do not consider thin peats (<50 cm) in our inventory and we conservatively assume 52% peat organic carbon content. However, even at 70.2 Pg C the WSL represents a substantial Holocene carbon sink, averaging 6.1 Tg C yr^{-1} over the past ~11.5 ka. However, a strong peak in peatland initiation in the WSL between 11,500 and 9,000 cal yr B.P. also coincides with increased levels of atmospheric methane attributable to high-latitude sources in the Northern Hemisphere. The release of carbon from long-term storage in northern peatlands, particularly if it involved the generation of methane, would have a significant impact upon atmosphic carbon and climate change.

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High-Resolution Imagery and Terrain Model for Collaborative Research of Environmental Change at Barrow, Alaska

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A broadly collaborative effort is nearly complete for creation and distribution of high-quality geospatial datasets to benefit research concentrated near Barrow, northernmost Alaska. The data include: OrthoRectified Radar Imagery (ORRI, 1.25 m pixels), a Digital Elevation Model (DEM, 5 m grid cells with <1 m vertical accuracy), and QuickBird satellite imagery (70 cm panchromatic; 2.8 m multispectral). The airborne-radar and satellite imagery were successfully acquired in late July and early August 2002. The data are currently being finalized by Intermap Technologies and DigitalGlobe. Release at full resolution to NSF-funded researchers, and at reduced resolution to the public, is expected by December 2003 (see http://instaar.colorado.edu/QGISL/barrow_high_res).

The spatial datasets are more precise, accurate, and useful than previously available data layers. The state-of-the-art, remote-sensing products will overcome obstacles of differing map projections, datums, resolution, extent, timeframe, accuracy, data format, and accessibility. The data will provide a long-lasting, common base for orthorectifying and georegistering other GIS data and imagery, and will establish a temporal baseline for decades of change-detection studies. Beyond education and outreach, the data should promote quantitative analysis, modeling, and collaboration in the fields of: ecosystem classification, health, and dynamics; terrestrial-atmospheric fluxes of greenhouse gases; natural and anthropogenic landscape dynamics; archeology; stream and thaw-lake hydrology and change; coastal flooding; coastal erosion; permafrost melting; and other environmental responses to unprecedented arctic warming. These societally relevant topics can be addressed in new ways and with greater success using shared digital topography and imagery.

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Trends and Variability in Pan-Arctic Springtime Thaw Monitored with Spaceborne Microwave Remote Sensing

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Land surface seasonal transitions between predominantly frozen and thawed conditions occur each year over roughly 50 million square kilometers of Earth's Northern Hemisphere, profoundly affecting surface meteorological conditions, ecological trace gas dynamics, and hydrologic activity. Spatial and temporal variability in the timing of spring thaw is a major driver of regional vegetation activity and net carbon exchange with the atmosphere at high northern latitudes.

The ability to quantifiably apply multi-year observations of landscape freeze-thaw status of one- to two-day temporal fidelity to ecosystem process studies in high-latitude regions will allow improved assessment of modeled processes for long-term monitoring. We employ radar backscatter measurements from the SeaWinds-on-QuikSCAT scatterometer and brightness temperature measurements from the Special Sensor Microwave Imager (SSM/I) and the Scanning Multichannel Microwave Radiometer (SMMR) to examine trends in the timing of springtime thaw across the pan-boreal high latitudes since 1979. We apply a temporal discrimination technique to these data sets to examine the timing of significant springtime thaw events across the Arctic Basin and Alaska. We apply data from biophysical monitoring stations to quantify the sensitivity to surface freeze-thaw state transitions and associated vegetation biophysical processes under a variety of terrain and landcover conditions. We develop a time series of landscape freeze-thaw products at regional and pan-boreal scales across multiple years. These time series products demonstrate the highly complex spatial and temporal nature associated with these critical processes.

Results show a trend toward an advance in pan-boreal springtime thaw over the past years, corroborating similar findings relating to advance in vegetation green-up. The continued capability for monitoring seasonal freeze-thaw cycles across the pan-boreal region provides a means for assessing inter-annual variability and, eventually, longer-term trends in ecosystem function.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, and the University of Montana under contract with the National Aeronautics and Space Administration.

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Warm Times/Cold Times in Iceland: Are the Last 500 Years Representative of Holocene Climate Variability?

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Situated at the boundary between major oceanic and atmospheric circulation systems, Iceland occupies a strategic position to monitor climate across much of the northern North Atlantic region. Estimates from historical records suggest Little Ice Age summers may have been 3° to 4° C colder than present, half the full glacial/interglacial temperature change for most of the planet. Erosion rates in the basaltic terrain of Iceland are relatively high, and many Icelandic lakes have thick lacustrine sequences that have accumulated over the past 10,000 to 15,000 years. The sediment records in deep Icelandic lakes are 15- to more than 50 m thick, and provide high-resolution archives of environmental change. To capitalize on these archives we used NSF's GLAD-200 coring system to recover continuous sediment cores from three deep lakes in Iceland during the summer of 2003. Hestvatn records changes in the southern lowlands, Hvitarvatn is a glacier-dominated lake that records the status of Langjökull, one of the largest ice caps on Iceland, and Haukadalsvatn records changes in northern Iceland.

We propose to address arctic warmth on three fronts: 1) To reconstruct the status of Iceland's ice caps from changes in the physical properties of sediment accumulating in glacier-dominated lakes. Ice cap modeling will provide quantitative estimates of past summer warmth consistent with our reconstruction of the ice cap derived from the lake sediment study. 2) To reconstruct the $d^{18}O$ of precipitation from the $d^{18}O$ of chironomid (midge) head capsules, a common constituent of arctic lake sediment. $d^{18}O$ of arctic precipitation is highly correlated with mean annual air temperature, providing quantitative temperature reconstructions. Chironomid $d^{18}O$ provides quantitative estimates of past air temperatures from arctic lakes, and circumvents persistent problems with low pollen productivity at high latitudes and with plant immigration delays. Changes in chironomid assemblages in the same sediment cores, tied to an Icelandic training set, will provide an independent estimate of summer temperature. 3) We will utilize paleoproductivity indices from Hestvatn and Haukadalsvatn to reconstruct the range of natural climate variability in a south-north transect across Iceland.

Preliminary results from Hvitarvatn indicate that calving glaciers entered the lake only during the Little Ice Age. Ice cap erosion appears to have been active through much of the middle and late Holocene, but environmental conditions were different in the early Holocene. The upper portions of the Hvitarvatn cores are varved, and variations in varve thickness will provide annual records of summer temperature variations over the past 1,000 to 2,000 years. Diagnostic tephras aid the geochronology.

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The SEARCH for New DEMs in the Arctic

Matt Nolan University of Alaska Fairbanks

In recent years, nearly all of Earth's land surface below 60°N latitude (including Antarctica) has been remapped topographically using modern techniques, resulting in digital elevation models (DEMs) with significantly greater accuracy and resolution than are now available in the Arctic. Accurate DEMs are essential to nearly every study that involves physical processes acting on land, and this case is even more true in the Arctic. Here, slight differences in aspect and slope can greatly affect biological, hydrological, and thermal dynamics, much more so than in temperate latitudes. Further, arctic topography has the potential to greatly change in response to climate warming, due to subsidence and thermokarst. Yet the highest-resolution DEMs available to scientists for Alaska are based on fifty-year-old maps and made with twenty-year-old digitizing techniques (roughly 60 m x 90 m postings); they often do not meet the USGS' own internal standards for accuracy. DEMs at even this coarse resolution are not commonly available for most of the remaining Arctic. It could be argued that the arctic region of planet Mars has DEMs that are easier to obtain and have better spatial continuity than the arctic region of planet Earth. As scientists involved with the first coordinated inter-agency effort to study the effects and feedbacks of climate change in the Arctic, I believe that we owe it to our sponsors and to future generations of scientists to push for the acquisition and utilization of new high-resolution and high-accuracy DEMs of Alaska and the Arctic for our research.

The technology now exists to rapidly and efficiently acquire new DEMs of the Arctic at accuracies and resolutions roughly one order of magnitude better than currently available, namely 5-meter postings with better than 2-meter vertical accuracy. These airborne SAR interferometric systems also deliver an associated ortho-rectified image at 1.25-meter posting, which can be fused with free Landsat imagery to create color images with stunning detail.

This poster will present examples from four independent applications demonstrating how such DEMs can significantly improve our understanding of important arctic processes.

- Arctic Hydrology: New DEMs have allowed us to create accurate stream channel networks used in modeling, and analyze tundra ponds and pingos with unprecedented accuracy.
- Arctic Soil Moisture: New DEMs allow us, for the first time, to extract a soil moisture signal using SAR interferometry, by reducing the noise created by uncertainty in topography.
- Arctic Glaciology: Measurement of ice volume change in the Arctic can be done more efficiently by repeat acquisitions of DEMs, with much higher spatial coverage and accuracy than is possible with field work alone.
- Arctic Tectonics: High-accuracy displacement maps of the recent M7.9 rupture of the Denali fault in Alaska were made possible using SAR and new DEMs.

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Ecosystem Carbon Fluxes in Response to Experimental Warming Along Arctic Climate Gradients: Using the ITEX Network to Test Climate Change Responses

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Climate warming in the Arctic is expected to strongly affect the carbon balance of tundra ecosystems, but responses to warming undoubtedly will differ substantially among the different ecosystems in the Arctic. Although originally designed to evaluate warming effects on phenology and growth of individual plants and later communities, the standardized International Tundra Experiment (ITEX) warming treatments represent an outstanding opportunity to examine ecosystem function in response to warming across temperature and moisture gradients. As part of the North American ITEX project (NATEX), we initiated measurement of carbon fluxes on the ITEX warming experiments across the latitudinal and moisture gradients represented by our sites (Alexandra Fiord, Barrow, Atqasuk, and Toolik). Alexandra Fiord is a high-arctic oasis; Barrow has a coastal high-arctic climate regime, whereas regimes of Atqasuk and Toolik are low-arctic continental. Fluxes were assessed using static chamber techniques conducted over 24-hour periods sampled regularly throughout the summer of two or three years at all sites. At Toolik, warming increased carbon losses at both moist and dry sites. In contrast, at both Atqasuk and Barrow, warming increased carbon uptake at wet sites and increased carbon losses from dry sites. At Alexandra Fiord, warming increased uptake at moist sites, but for both wet and dry sites the response depended on the sample year. In both wet and dry sites in Alaska, warming increased gross photosynthetic uptake, even in sites that had greater net carbon losses with warming. The results indicate that the respiration response to warming determines whether the carbon balance of a site becomes more positive or negative with warming.

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Rain-On-Snow Events Impact Soil Temperatures and Affect Ungulate Survival

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Field data from Spitsbergen and numerical modeling reveal that rain-on-snow (ROS) events can substantially increase sub-snowpack soil temperatures. However, ROS events have not previously been accounted for in high-latitude soil thermal analyses. Furthermore such events can result in widespread die-offs of ungulates due to soil surface icing. The occurrence of Spitsbergen ROS events is controlled by the North Atlantic Oscillation. Globally, atmospheric reanalysis data show that significant ROS events occur predominantly over northern maritime climates, covering 8.4 x 106 km^2. Under a standard climate-change scenario, a global climate model predicts a 40% increase in the ROS area by 2080–89.

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Linking *Cassiope tetragona* Growth and Reproduction to High Arctic Cimate and the Arctic Oscillation

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In this study, we report the initial results of an investigation of the relationships between *Cassiope tetragona* growth and reproduction chronologies from sites on central Ellesmere Island, Canada, with climate variables recorded at the Eureka High Arctic Weather Station (HAWS) (1948–96) and the summer Arctic Oscillation index (AOS) (1948–96). Using modified dendrochronological techniques, annual growth and reproduction chronologies were developed for sites at Hot Weather Creek (HWC) and Alexandra Fiord (AF), Ellesmere Island.

Correlation analysis showed that, in general, the AF and HWC chronologies were positively correlated with average air temperature and negatively correlated with total monthly precipitation at Eureka HAWS during the growing season (June–Sept). In addition, the chronologies were negatively associated with the AOS index for the period 1948–96. Furthermore, high AOS index values were negatively correlated with average air temperature and positively correlated with total precipitation during the growing season. High AOS index values appear to be associated with a small decrease in *C. tetragona* growth and reproduction from 1948–96. Thus, when the AOS index is in the positive phase (high index values), cooler and wetter conditions may predominate in the Canadian Arctic during the growing season, which in turn may lead to reduced growth in *C. tetragona*. Future investigations will address the relationship between *C. tetragona* growth and reproduction and phase changes in the AOS index values throughout the 20th century.

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Relationship Between Plant Biomass and Arctic Tundra Bioclimate Subzones, Based on the Circumpolar Arctic Vegetation Map

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The Circumpolar Arctic Vegetation Map (CAVM) was used to analyze the relationship between plant biomass and arctic tundra bioclimate subzones. The AVHRR satellite data on which the map was based were used to calculate NDVI (normalized difference vegetation index). NDVI was in turn used to calculate aboveground plant biomass (phytomass), based on clip harvest data.

Five bioclimate subzones of the Arctic Tundra Zone were mapped: A through E, from north to south. Average phytomass density increases from subzone A to E, but not as much as would be expected in subzone C. Phytomass density increases 80–100% with each subzone change to the south, except for subzone C where the increase is only half as much. This is partly due to higher average elevation in subzone C compared with other subzones. Phytomass density in the Arctic decreases with elevation, even without controlling for subzones. Another factor is the large area of subzone C that occurs in Canada. Canada, Svalbard, and Greenland, which were all recently glaciated, have lower phytomass densities in all subzones than Alaska and Russia, which were mostly unglaciated.

In conclusion, bioclimate subzone alone is not a good predictor of phytomass. It is related to phytomass on zonal sites, but factors such as elevation and glacial history also play a large role in controlling phytomass. All of these factors were combined in the intergrated mapping process which was used to map the vegetation units of the CAVM.

*A large portion of this analysis was completed by Jonathan Burian as part of a Research Experience for Undergraduates (REU) summer project.

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Spatial Variability of the Active-layer Thickness: Observations, Analysis, and Modeling

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The uppermost layer of seasonal thawing above permafrost (the active layer) is an important regulator of energy and mass fluxes between the surface and the atmosphere in the polar regions. A major difficulty in predicting and mapping active-layer thickness stems from its large spatial variability over a wide range of geographic scale, in response to many interacting climatic and terrestrial factors. Here we address the problem of spatial and temporal variability of active-layer thickness over a wide range of scales, and the landscape-specific effects of this variability in several environmental settings.

Data from eight years of extensive, spatially oriented field investigations conducted in north-central Alaska are used to examine regularities in thaw depth for several landscape types and to provide a comprehensive evaluation of spatial and temporal active-layer variability under contemporary climate. The results can be used to facilitate detailed characterization of active-layer thickness at small geographical scale, to evaluate currently available spatially distributed permafrost models, and bridge a critical gap between models of climate-permafrost interactions and localized thaw-depth measurements.

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Toward Assessment of the Role of Physical/Chemical Processes in Soil Carbon Cycling in the High Arctic: Thule, Greenland

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The ice-free area of the high Arctic covers an area approximately two-thirds that of the low Arctic, and it contains approximately one order of magnitude less organic carbon, according to sparse available data. Due to cryoturbation, mineral and organic soil horizons are disrupted, and organic matter is transported to depth and mineral soil to the surface. It is assumed that increases in air temperature have strong impacts on high-arctic ecosystems, but lack of detailed information on coupling of physical, chemical, and biological processes in the upper soil surface (active layer) makes the assessment of the impact of climate change difficult.

In conjunction with ecological and microbiological investigations, our study focuses on the influence of physical processes (frost heave, textural sorting, gelifluction) on organic carbon storage and physical/chemical weathering processes in high-arctic soils. The study area is located at the Thule Air Base on northwest Greenland (76°N, 68°W), where complete climate records from pre-1978 to the present indicate increases in air temperature and precipitation during the past nine years. The area is composed of carbonates, sandstone, basalt, and gneiss overlain by glacial drift deposits. Three major plant community types occur with increasing vegetation coverage: 1) polar desert, 2) polar semi-desert, and 3) polar fens. Sorted/unsorted nets, circles, and stripes are common surface expressions.

Two automated soil and microclimate stations for year-round monitoring of soil moisture and soil temperature, relative humidity, air temperature, incoming radiation, net radiation, wind speed and direction, and rain and snowfall were installed in polar desert and polar semi-desert sites. To account for changes in snow accumulation, summer rainfall and surface temperature, heating and watering experiments along with snow fences are set up and monitoring is performed in the fenced and control sites. The soil measurements are completed by discharge measurements of streams draining the study sites. To estimate weathering flux, soil and stream water will be collected during thaw season using suction lysimeter and analyzed for major and trace elements. Sr isotope ratios and stable isotopes of water and carbon will be used as tracers to quantify chemical and physical processes. To better assess the carbon content in high-arctic soils and its relation to cryoturbation, lithology, and toposequences, soil pits will be excavated, sampled, and analyzed for grain size distribution, chemistry, and organic C and N content.

We will present an introduction and first results of our study that started this year with the first field campaign.

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Paleolimnological Evidence for Recent Environmental Changes in Arctic Lakes from Northeastern European Russia

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General circulation models predict that warming in the Arctic will occur more rapidly than elsewhere, and there is growing evidence from palaeoclimatic studies that unprecedented climate warming has already taken place in many parts of the Arctic during the 20th century. Lake sediment records in these regions are especially useful in identifying the extent of warming.

Here we examine results from the Pechora region of the Russian Arctic and assess evidence for climate change. We have obtained surface sediment and short sediment cores from over thirty lakes in the Pechora and Usa basins which have been dated using a mixture of ^{210}Pb, Pu, and SCP profiles. Diatom and chironomid analyses have been used to determine the extent and direction of recent change, and SCP profiles have been used to assess the timing and extent of pollution. Diatom and chironomid floristic changes recorded in the sediments of the studied lakes over the past decade may have been caused by both climate warming and air-borne pollution or a combination of the two. A number of statistical methods were applied to evaluate the cause of the changes. Instrumental climate records were used to assess, statistically, the amount of variance in diatom and chironomid data explained by climate; comparisons with modern plankton data from these sites were used in an attempt to explain the causes of change.

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In Situ Warming Chambers Stimulate Early Season Production of *Eriophorum vaginatum* Leaves and Roots

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Student Poster

We examined the effects of passive open-top warming chambers on weekly leaf and root production in a moist tussock tundra near Toolik Lake, Alaska. The warming of chamber air was broadly consistent with the magnitude and seasonality observed in recent decades throughout northwestern North America. Within the chambers, early-season leaf production rates were higher, maximum rates in each leaf cohort occurred earlier, and peak biomass was observed twenty days earlier than under ambient conditions. Consequently, plants within the chambers maintained more live leaf biomass during the period of highest photosynthetically active radiation. However, there was no evidence of a change in annual aboveground production. Similarly, early-season root production rates were higher, maximum production rates occurred earlier, and significantly greater live root biomass was observed by mid-July within the chambers. Consequently, plants within the chambers maintained more root biomass during the period of highest nutrient availability. Annual belowground production may have increased, as shown in previous laboratory experiments, but the evidence was tentative.

Rates of leaf and root production showed an inverse relationship under ambient conditions, but this broke down and became weakly positive in the chambers. In both instances the relationship persisted throughout the snow-free period. This may have been a response to chamber effects on either the availability of or the demand for resources. Regardless, our data suggest that open-top chambers improved plant resource economies and that the effect was sustained beyond the early-season period of maximum warming.

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Photography-based Measurements of the Expansion of Shrubs in Northern Alaska

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Student Poster

In the late 1940s, several thousand low-altitude oblique aerial photographs were taken, covering the North Slope Uplands and Brooks Range regions of Alaska. Over the past four summers, 270 of the old photos have been repeated from helicopter. The area visible in the repeated photographs covers over 2,000 km^2, including sections of eighteen major drainages and areas of open tundra. With few exceptions, photos in which there were shrubs present in the 1940s show an increase in shrub size, patch density, and areal extent in the past fifty years. A grid system overlay has been used to analyze 150 of the photo pairs quantitatively. This analysis indicates an increase of 20 (provisional) km^2 in the areal coverage of shrubs. The photo analysis also shows that while alder is the most photographically conspicuous shrub contributing to the expansion, willow and birch are also involved. We are currently using data from aboveground shrub biomass harvests to translate the change in areal coverage of shrubs represented by the expansion into an increase in aboveground shrub biomass.

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Biocomplexity of Frost Boil Ecosystems: Models for Analyzing Self-Organization Across the Arctic Bioclimate Gradient

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Frost boils are small, often regularly spaced, barren or sparsely vegetated circular patches that develop in the Arctic through processes of frost heave. They appear to be particularly sensitive to differences in climate. These features occur on most level surfaces with moderate site conditions and offer an opportunity to study the response of disturbed and undisturbed surfaces across the full arctic bioclimate gradient.

Frost-boil morphology varies dramatically across the arctic bioclimate gradient due to complex interactions between the physical and biological components of the system (ice lenses, soils, and vegetation). Biogeochemical cycling within the soil is affected by a combination of biological and physical processes operating within the boil. A vegetation succession model (ArcVeg) describes how vegetation responds to differences in climate and disturbance regimes. A differential frost-heave (DFH) model describes the physical processes involved in the self-organization of frost boils. A conceptual model shows how the strengths of the various interactions between the physical and biological components vary under different climate regimes. A major goal of the project is to link the physical and biological models to help explain how frost heave, in concert with the vegetation, responds to differences in climate and disturbance regimes.

Starting in 2002, a team of researchers from the U.S. and Canada began studying frost-boil ecosystems at a network of eleven study sites along a transect from Happy Valley, Alaska, to Ellef Ringnes Island, Canada, and at two sites in Russia. The interdisciplinary project has five major components: Climate and Permafrost, Soils and Biogeochemical Cycling, Vegetation, Ecosystem Modeling, and Education (See abstract by Gould and Walker regarding integrating frost-boil biocomplexity science and education). Vegetation, active layer, and snow depth have been mapped in eighteen 10 x 10 m grids. Climate stations, soil-heave monitoring, and detailed soils descriptions and analysis have been conducted at all the research grids.

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The Circumpolar Arctic Vegetation Map: A Tool for Analysis of Change in the Arctic

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The Circumpolar Arctic Vegetation Map portrays the vegetation north of the arctic tree line. Here we present the map with an area analysis. Fifteen vegetation types are mapped based on the dominant plant growth forms. More detailed, plant-community-level information is contained in the database used to construct the map. The reverse side of the vegetation map has a false-color infrared image constructed from Advanced Very-High Resolution (AVHRR) satellite-derived data, and maps of bioclimate subzones, elevation, landscape types, lake cover, substrate chemistry, foristic provinces, the maximum normalized difference vegetation index (NDVI), and aboveground phytomass.

The vegetation map was analyzed by vegetation type and biomass for each country, bioclimate subzone, and floristic province. Biomass distribution was analyzed by means of a correlation between aboveground phytomass and the normalized difference vegetation index (NDVI), a remote-sensing index of surface greenness. Biomass on zonal surfaces roughly doubles within each successively warmer subzone, from about 50 g m^{-2} in Subzone A to 800 g m^{-2} in Subzone E.

But the pattern of vegetation increase is highly variable, and depends on a number of other factors. The most important appears to be the glacial history of the landscape. Areas that were glaciated during the late Pleistocene, such as Canada, Svalbard, and Greenland, do not show such strong increases in NDVI with temperature as do areas that were not glaciated. Abundant lakes and rocky surfaces limit the greenness of these recently glaciated surfaces. The highest NDVI and phytomass are found in non-glaciated regions of Alaska and Russia. Soil acidity also affects NDVI patterns. In Subzone D, where the NDVI/soil acidity relationship has been studied most closely, NDVI is greater on acidic surfaces.

This has been attributed to fewer shrubs and higher proportion of graminoids (more standing dead sedge leaves) on the nonacidic surfaces. The trend of higher NDVI on acidic surfaces holds for subzones A, B, and C, and is probably caused by generally drier soils, with less production, on limestone-derived soils of the Canadian Arctic. The trend is less clear in Subzone E because of much fewer nonacidic surfaces, and the abundance of glacial lakes with low NDVI on the acidic shield areas of Canada. Future analyses of the circumpolar database will be directed at examining which geographic regions and vegetation types have shown the strongest increases, and how these are correlated with temporal temperature changes.

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Coupling of Carbon and Water in High-Arctic Ecosystems

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We are quantifying the coupling of the carbon and water cycles and the interacting physical, chemical, and biological (PCB) processes that control C exchange between cold, dry, terrestrial ecosystems and the atmosphere. We are focusing on cold, dry ecosystems because: 1) understanding of carbon and water interrelationships and net C exchange is only rudimentary for this extreme environment, making it impossible to predict the vulnerability of this ecosystem to the expected anthropogenically exacerbated warming; 2) these tundra systems are sufficiently simple, allowing the quantification of all key components and the development of a system-behavior conceptual model, and 3) the vital role of unfrozen water in this cold, dry environment underlies the importance of thresholds (e.g., 0° C is a distinct threshold for water availability) and highly nonlinear interactions between PCB processes. Our discoveries will contribute to the understanding and the quantification of global carbon and water cycling, as well as to the understanding of extreme habitats on Earth.

We are focusing on three levels of biocomplexity. First, we quantify the seasonal changes in the coupling of C and water at the leaf and ecosystem scales using in situ isotopic ($d^{13}C$ and $d^{18}O$) approaches. Second, we evaluate and quantify how the seasonal patterns of physical (soil temperature and soil water), chemical (soil solution and weathering) and biological (microbial and vegetation) processes interact to regulate the dynamics of net C exchange. Third, we will use a biogeochemical model (TEM) to investigate net CO_2 exchange and the complex PCB interactions under current climates, and a range of likely future climate change scenarios, and integrate these with arctic and global carbon budget estimates. Our program will be based on articulating the complexities of carbon and water coupling under current conditions, but also on the responses of the biological, chemical, and physical processes and interactions in response to field manipulations of winter and summer precipitation (increases) and warming (+2 and +4° C). This experimental approach is the means by which we can evaluate the interactions and nonlinearities of carbon and water coupling, net carbon exchange, and PCB processes.

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Groundwater Discharge and Periglacial Processes in the Foothills of the Brooks Range, North Slope, Alaska

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More than 30,000 liters/sec. of spring water discharge along the eastern part of foothills of the Brooks Range, North Slope, Alaska. These springs flow year-round and cover wide areas with aufeis every winter. Aufeis is among the biggest temporary storage of freshwater during the winter period (more than eight months). This study examines the historical volume of the aufeis using aerial photographs and satellite imagery as well as MODIS Airborne Simulator (MAS).

The energy balance of the aufeis is an important parameter for estimating perennial aufeis formations. We estimate the Holocene ice volume of aufeis using $CaCO_3$ deposits in the soil. Carbonate material distributions and ^{13}C isotope enrichment signals are indicative of the area occupied by aufeis. Thermal enrichment of the ^{13}C spring water was around 0 to -2 permil at the Hulahula River aufeis area. The ^{13}C isotope of the area immediately outside the aufeis field is around –25 permil and is also very low in carbonate content. The isotope distributions reveal the quaternary history of the springs' discharge and temperature. Some carbonate deposits indicate aufeis fields were much bigger in the past, caused by more limited sublimation and reduced thawing during the summer. Some of the aufeis would be able to survive during the last glacial maximum.

Questions about the spring water's ground residence time and infiltration processes are also examined in this study. We collected water from springs, wells, surface water, and precipitation samples for isotope (C, O, H, Sr) and chemical analyses. Preliminary results indicated most of the spring water might come from upper south-facing slopes of the Brooks Range (limestone areas). Infiltrated meteoric water percolates along the fault between Paleozoic sedimentary rocks and Permo-Triassic sedimentary rocks. The Kuparuk aufeis (spring) may not follow the same path as other springs. A multiple-member mixing model was used to estimate the residence time of groundwater. A ^{13}C model indicated the water flowing from the Saviukviayak River spring was about 2,000 years old.

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Variability in the Arctic Ocean: 1948-1993

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We have developed a new statistical reduction of the Arctic Ocean data set that was released earlier under the Gore-Chernomyrdin environmental bilateral agreement, and which was in the form of decadal gridded fields. Our new reduction provides annual resolution of temperature and salinity in a set of thirteen boxes covering the Arctic Ocean during 1948–93, as well as additional nutrient information.

In this study we examine interannual variability with respect to three issues: the salinity of the upper ocean, the temperature of the Atlantic layer, and, to a lesser degree, the extent of Pacific waters within the Arctic Ocean.

We find:

- Evidence for a long-term and basin-wide transition to more saline conditions in the upper Arctic Ocean about 1976;
- That the additional upper ocean salinity increase in the Eurasian Basin beginning about 1989 likely did not originate on the Kara and Laptev shelves;
- That the Atlantic layer warmed significantly in the 1950s and 60s, and cooled in the 1970s;
- That the phase propagation of these temperature anomalies is uncertain, contrary to that of the strong warming beginning in the late 1980s, which has been carried throughout much of the Arctic Ocean by the prevailing circulation;
- That the Pacific waters, as indicated by the silicate maximum in the halocline, disappeared abruptly from the Makarov Basin in the mid-1980s.

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Polar Marine Mammal Habitat Use May Reflect Climate Change

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Meso-scale oceanic features such as the marginal sea ice zone, hydrographic frontal systems, and biological productivity often correspond to high densities of upper-trophic-level predators. In the Bering, Chukchi, and Beaufort Seas the distribution and foraging activity of marine mammals reflects the location of such zones. Water column-foraging mammals (e.g., ringed seals, beluga, and bowhead whales) are commonly associated with oceanographic fronts, such as those at the continental shelf-slope boundary and along the marginal ice zone. Benthic-foraging mammals (e.g., bearded seals and gray whales), on the other hand, are likely to be found in areas of high benthic productivity on the continental shelf, presumably related to carbon deposition rates.

Understanding the principal factors that influence the ecological partitioning of these various habitats by marine mammals will improve our ability to detect and predict potential changes in ecosystem dynamics due to climate change or other environmental impacts. In particular, the dramatic thinning of sea ice over the past twenty-five years suggests that large ecological changes can be anticipated in the future for populations associated with sea ice communities.

For example, the extent to which some pinniped species are tied to sea ice habitats throughout the year is known to vary (spotted seals haul out in coastal terrestrial habitats on the Bering Sea's Russian and Alaskan coasts during summer, but it is unknown where ribbon seals go when the Bering Sea is ice free). Similarly, seasonal shifts in sea ice and oceanographic conditions are likely to affect the distributions of both bearded seals, which favor productive benthic foraging zones, as well as ringed seals and beluga whales, which seek aggregations of prey in the water column and under ice. Because of the importance of sea ice in the life history and ecology of these species, they may be particularly vulnerable to climatic change due to warming over the next several decades.

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Biological Implications of Arctic Change

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Studies in the northern Bering and Chukchi Seas over the last two decades provide many indications of ecosystem change. The tight pelagic-benthic coupling observed between seasonal water column carbon production processes and underlying short- and long-term benthic carbon transformation processes provide a "footprint" in the sediments of persistent ecosystem events and subsequent time series changes. Pelagic-benthic coupling can be studied via underlying sediment processes on various time scales. Sediment metabolism can be an indicator of weekly-to-seasonal carbon depositional processes, while benthic faunal populations can act as multi-year, long-term integrators of a variety of marine processes. This detection of biological changes in the marine environment coincides with recent observations of arctic environmental changes, including a seasonal reduction in the extent and duration of sea ice, increased seawater temperature, and changing hydrographic conditions. Thus, high-latitude ecosystems appear particularly sensitive to climate change, and the shallow, productive nature of the Bering Strait region in the North American Arctic may provide a sentinel indicator of global change effects.

For example, recent studies show that the northern Bering Sea is shifting toward an earlier spring transition between ice-covered and ice-free conditions. Coincident changes in the timing, extent, composition and location of annual production, both primary and secondary trophic levels, can lead to dramatic ramifications for higher-trophic-level fauna utilized by indigenous populations in the Arctic, such as benthic-feeding walrus, bearded seals, gray whales, and diving seaducks. Within the Bering Strait Long-term Observatory project, time series sites have been continued south of St. Lawrence Island, in the middle of Chirikov Basin south of Bering Strait, and just north of Bering Strait in the southern Chukchi Sea. An overall decline in both sediment oxygen uptake (an indicator of carbon supply to the sediments) and overall benthic standing stock from the 1980s to the present has occurred in this region, with subsequent ramifications to higher trophic organisms that use benthic prey. Declining bivalve populations south of St. Lawrence Island indicate a decline in the bivalve prey source for the diving spectacled eider, with indications that a change in hydrographic forcing and nutrient supply is limiting primary production in the region. Recent studies of gray whale feeding areas and time series measurements at select stations in the Chirikov Basin north of St. Lawrence Island also indicate a decline in the benthic amphipod prey biomass in the region over the past decade, with indications that gray whales are dispersing north of Bering Strait into the Chukchi Sea, and also feeding in new areas along their migration path to obtain food.

Thus, biological systems are detecting ecosystem change on the shallow shelves of the northern Bering and Chukchi Seas, which are intimately connected to systems farther to the north. Current studies as part of the Western Arctic Shelf-Basin Interactions (SBI) global change project are investigating the production, transformation, and fate of carbon at the shelf-slope interface in the northern Chukchi and Beaufort Seas, downstream of these productive shallow western arctic shelves, as a prelude to understanding the impacts of a potential warming of the Arctic. As SEARCH moves into the implementation phase, it seems logical that international time series shelf-slope transects be maintained at key locations throughout the Arctic to detect change in this critical ecosystem.

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Distribution, Growth, and Reproduction of Zooplankton in the Northern Barents Sea in Spring—Consequences for Global Change Scenarios

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Reproduction and growth of the dominant copepods *Calanus finmarchicus*, *C. glacialis*, *C. hyperboreus*, and *Pseudocalanus minutus* were studied on transects across the sea ice zone of the northern Barents Sea in May and June, 1997. *C. glacialis* and *C. finmarchicus* were numerically dominant and also the largest component of the biomass. *C. hyperboreus* was rather rare. Moderate levels of phytoplankton, and eventually, high concentrations of ice algae, supported maximum egg production rates of 53.6 and 48.5 eggs female^{-1} d^{-1} of *C. glacialis* in May and June, respectively. Results of incubation experiments were supported by a tremendous abundance of *C. glacialis* eggs in the water column ranging from 7 x 103 to 4.4 x 104 m^{-2} in May and from 9.8 x 103 to a maximum of 9.7 x 104 m^{-2} in June. In contrast, *C. finmarchicus* spawned only in the vicinity of the ice edge at a maximum rate of 30 eggs female^{-1} d^{-1}. Egg sacs of *P. minutus* were often observed in the preserved samples but contained only few eggs, which may be due to loss during sampling. The presence of considerable concentrations of young stages in May and June indicated successful recruitment of *C. glacialis* and *P. minutus* in early spring. Based on these observations we discuss potential responses of the zooplankton community of the Barents Sea to the expected warming due to climate change.

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Variability of Ice and Ocean Fluxes in the Arctic/Sub-Arctic Domain

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Observations and results of coupled ice-ocean models reveal a large variability of fluxes exchanging heat, freshwater, and volume between the arctic/sub-arctic basins and with the North Atlantic Ocean.

The comparison of several decades of model simulations with long time series of hydrographic measurements at key locations and with satellite observations give some confidence in the model derived cause/effect relationships.

We will give an overview over some of the recent findings with respect to the evolution and spreading of heat and salt anomalies entering or leaving the Nordic Seas and the Arctic Ocean from more than five decades of coupled ice-ocean model simulations. We will also address the dominant modes of simulated and observed ice-cover variability. Both phenomena are influenced by local and far-field forcing and interact with each other.

The resulting effects on water formation and the dense water outflow from local to arctic/sub-arctic basin scale will be discussed.

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Spatial and Temporal Variability of Oceanic Heat Flux in the Arctic

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Models indicate that the equilibrium mean thickness of the arctic ice pack may be sensitive to small changes in annual average oceanic heat flux (F_w), but the sparseness and variability of direct observations has made it difficult to produce credible regional estimates at annual and longer time scales. In order to obtain a better understanding of the large-scale structure and temporal variability of F_w in the Arctic, observations of heat in the mixed layer and ice dynamics are compared with parameterizations and climatologies.

First, long-term drifting platform observations of temperature and salinity (primarily from SALARGOS and IOEB buoys) are used to describe the annual cycle of temperature above freezing (T_{af}) in the mixed layer beneath arctic pack ice between 1975 and 1998, and estimate F_w by modulating the observed T_{af}s with ice-ocean friction velocities (u*) determined from the platform drifts. In the Transpolar Drift, T_{af} is not negligible in winter, which implies a positive F_w to the ice pack by means other than solar heating. In the Beaufort Gyre, variability of T_{af} (and F_w) between different years is apparent and sometimes not negligible in winter.

Next, a parameterization based solely on the solar zenith angle (with a one-month lag) is found to largely describe the observed T_{af}s (with root-mean-square error less than 0.05° C), despite the lack of an albedo or open-water term. Correlations between the observed annual T_{af}s and the parameterization are high (median $R^2 = 0.75$), compared to T_{af}s determined from a hydrographic dataset based on the US-Russian EWG Atlas (median $R^2 = 0.16$). Deviations of observed T_{af}s from the parameterization cannot consistently be explained by local open-water fraction anomalies (determined from satellite ice concentration data), but are likely due to heat advected horizontally, or entrained from below the halocline (such as from synoptic storms).

Finally, a monthly F_w "climatology" from 1979 to 2002 is produced by modulating parameterized T_{af}s with u* based on daily ice drift estimates from a composite AVHRR, SSMI, and IABP data set. Correlations are moderate between the derived climatology and Fw estimates from the drifting observations (median $R^2 = 0.52$). Although the interannual variations in T_{af} are fixed by the parameterization in the derived climatology, the dynamics cause an overall positive trend in arctic F_w after 1989, except in the southern Beaufort Sea.

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Climate Impact on the Barents Sea Ecosystem

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Physical factors that make arctic marine ecosystems unique are a very high proportion of shallow continental shelves, dramatic seasonal change, generally low insolation, low temperature, extensive permanent and seasonal ice-cover, and a large supply of freshwater from rivers and melting ice. Because of these conditions, many of which are challenging for marine biota, arctic marine ecosystems have a large number of specialists, many of which are not found elsewhere. These organisms have through time been able to adapt to the arctic environment, but they are still challenged by extreme inter-annual variations. A large legacy from past data collection in combination with present-day modeling shows that climate variability can influence population parameters of marine organisms. Without doubt, water temperature has impact on species composition in different areas, and recruitment, growth, distribution, and migration of different fish species. Most of the relationships between temperature and population variables, however, are qualitative; thus few relationships have been quantified.

Although the AO is defined circumpolarly and the NAO (North Atlantic Oscillation) only for the North Atlantic region, the two are highly correlated. The NAO may be regarded as the North Atlantic branch of the AO. In this presentation the role of the NAO/AO in determining the ocean climate and ecology of the Barents Sea will be explored. Fish recruitment seems to be closely linked to climate variability, and feeding distribution of cod, haddock, and capelin depends on the climatic conditions, with more easterly and northerly distributions noted in warm years than in cold ones. The growth of fish also seems to depend on the environmental temperature, but the temperature-growth relationship is probably not simple. The climatic fluctuations also influence the plankton production and thereby the food conditions for all plankton feeders. Temperature effects linked to the variability of food may therefore be as important as the direct effect of temperature on the biological conditions of fish.

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Sea Level Change in the Russian Sector of the Arctic Ocean

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Sea level is a natural integral indicator of climate variability. It reflects changes in practically all dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin. The use of estimates of eustatic sea level rise as an indicator of climate change therefore incurs the difficulty that the inferred sea level change is the net result of many individual effects of environmental forcing. Since some of these effects may offset others, the cause of the sea level response to climate change remains somewhat uncertain. This paper is focused on an attempt to provide first order answers to two questions, namely: What is the rate of sea level change in the Arctic Ocean? and furthermore, What is the role of each of the individual contributing factors to observed Arctic Ocean sea level change? In seeking answers to these questions we have discovered that the observed sea level is rising over the Arctic Ocean at a rate of approximately 0.123 cm/year and that after correction for the processes of the glacial isostatic adjustment this rate is approximately 0.185 cm/year. There are two major causes of this rise. The first is associated with the steric effect of ocean expansion. This effect is responsible for a contribution of approximately 0.064 cm/year to the total rate of rise (35%). The second most important factor is related to the ongoing decrease of sea level atmospheric pressure over the Arctic Ocean, which contributes 0.056 cm/year, or approximately 30% of the net positive sea level trend. A third contribution to the sea level increase involves wind action and the increase of cyclonic winds over the Arctic Ocean which leads to sea level rise at a rate of 0.018 cm/year or approximately 10% of the total. The cumulative effect of sea level rise due to increase of river runoff and a negative trend in precipitation minus evaporation over the ocean is close to 0. In this region it therefore appears that approximately 25% of the trend or 0.045 cm/year may be due to eustatic effect of increasing Arctic Ocean mass.

Abrupt Change in Deep Water Formation in the Greenland Sea: Results from Hydrographic and Tracer Time Series

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Long-term measurements of temperature, salinity, as well as the transient tracers tritium, ^3He, CFC-11, and CFC-12 have been used to study the renewal rates of deep water in the Greenland Sea. Early evaluation of the data sets revealed an abrupt change in deep water formation around 1980 with a drop in the deep water formation rate from ca. 0.5 Sv to 0.1 Sv. Whereas the data before 1990 were compiled from cruises of opportunity, annual cruises were conducted during the 1990s. The resulting time series allows us to deduce information on the change in water mass properties throughout the water column. In this contribution we explore if and how the observed changes in the hydrographic and tracer properties of the Greenland Sea are related to the forcing at the atmosphere/ocean interface. Additionally, we derive average and single-event related deep water formation rates during the 1990s. Finally, we discuss the impact of the change in deep water formation on the hydrography and the exchange of deep water between the Nordic Seas and the Arctic Ocean.

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The Impact of Climate Patterns on the Bering Sea Ecosystem

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The sub-arctic seas are influenced by hemisphere-wide patterns of climate variability. Changes in the 1990s in the Arctic Oscillation (AO) have brought warmer temperatures and more southerly winds over the Barents Sea in winter, and warmer temperatures over the eastern Bering Sea shelf in spring. The southern Bering Sea is also influenced by changes in the Pacific Decadal Oscillation (PDO). Changes in these large-scale climate patterns cascade through the ecosystem, modifying physical forcing, timing, and extent of the phytoplankton bloom, and community composition of upper trophic levels. One of the defining characteristics of the Bering Sea is the sea ice cover. Changes in the AO and PDO are associated with changes in the timing of the arrival of sea ice, its duration, and its extent. Over the southeastern shelf, the timing of ice retreat plays a critical role in determining the timing of the spring phytoplankton bloom. The presence of ice after mid-March results in an early phytoplankton bloom associated with presence of sea ice. The timing of phytoplankton bloom impacts the availability of food for zooplankton. The Oscillating Control Hypothesis addresses how different regimes (cold versus warm) impact the ecosystem, and in particular, the fisheries. Changes in large-scale climate patterns also influence the flow of water through the Aleutian Passes which brings nutrient-rich, warm water into the Bering Sea, and modifies the transport through Bering Strait, which is the only oceanic connection between the North Pacific and Arctic Ocean. Research focused on understanding how climate variability affects the ecosystems of the Bering Sea is critical.

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Toward the Next Generation of 3D Marine Ecosystem Models

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To predict the effects of global warming on ecosystem dynamics and the effects of those changes in ecosystem dynamics on biogeochemical cycles, oceanic CO_2 uptake, and fishery resources, we need to develop 3D global models which explicitly represent the dynamics of oceanic circulation, ecosystems, and fishes.

We developed a 3D ecosystem model for the sub-arctic North Pacific, NEMURO (North Pacific Ecosystem Model Used for Regional Oceanography), as members of PICES (North Pacific Marine Science Organization) Model Task Team, which includes phytoplankton and zooplankton divided into two and three groups, respectively. NEMURO has also been coupled with fish bioenergetics and population models for two pelagic fishes, Pacific saury and Pacific herring. Using data sets of observed climatology and simulated fields (CCSR/NIES model) as boundary conditions for our ecosystem model, we conducted preliminary experiments for demonstrating the effects of global warming on ecosystems and pelagic fishes in the sub-arctic North Pacific. The model results show increased vertical stratification and a poleward shift of the sub-tropic–sub-arctic front associated with global warming, causing decreases in biological production and stock size of Pacific saury. This is a good example demonstrating the impacts of global warming on ecosystem and fishery resources. We are also planning to simulate decadal variability of ecosystems, for model validation and to test hypotheses about linkage between climate shift and decadal variability of fish catch.

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Infaunal Community Composition and Biomass from the Gulf Of Alaska To the Canadian Archipelago: A Biodiversity Study

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Recent studies show that high levels of biodiversity can stabilize ecosystems. One consequence of high biodiversity is that it could increase resistance to extinction events caused by fluctuating environmental conditions such as a regime shift or global warming. Low-diversity regions such as the Arctic may be more susceptible to ecosystem destabilization because there are fewer key players in each functional group. However, knowledge of pan-arctic trends, and patterns of benthic infaunal biomass and biodiversity, has been limited by lack of historical benthic measurements in portions of the Beaufort Sea and the Canadian Archipelago. Standardized sampling techniques for measuring benthic carbon biomass were used to examine benthic community composition variations in the northern Bering and Chukchi Seas and stations in the Beaufort Sea and Canadian Archipelago. Benthic sediment and water column samples were taken along the continental shelf from the Gulf of Alaska, the Bering, Chukchi, and Beaufort Seas, and within the Canadian Archipelago as far east as Spence Bay, Nunavut.

Stations were grouped utilizing a statistical numerical clustering program based on the similarity levels of species abundance. Dominant taxa (macroinfaunal abundances, total wet weights, and organic carbon weights) were assessed. The Shannon-Weaver diversity index (H’) was used as a measure for biodiversity. In addition, sediment total organic carbon, modal grain size, chlorophyll *a* content, carbon to nitrogen ratios, and integrated water column chlorophyll *a* were measured.

Significant positive Spearman’s rho correlations were observed between macroinfaunal diversity and macroinfaunal organic carbon biomass, and also between macroinfaunal diversity and sediment C/N ratios. Similarity cluster analysis indicates groupings of stations that may be related to current flow. The patterns of environmental variables (integrated water column chlorophyll *a* concentration, sediment chlorophyll *a* content, TOC, C/N, sediment modal grain size) ranged widely among the four study regions. The Gulf of Alaska possessed the highest mean macroinfaunal abundances, but low species diversity and organic carbon biomass. The Bering and Chukchi Seas exhibited the highest mean benthic species diversity and organic carbon biomass. The Beaufort Sea exhibited the lowest mean benthic biomass and diversity. A large variation in parameters was observed in the Canadian Archipelago, which is consistent with the previous descriptions of the Canadian Archipelago as a "mosaic" of environmental interactions. Infaunal hot spots, with high benthic biomass, were observed in the Canadian Archipelago at Hat Island and Whale Bluff, comparable in organic carbon biomass to many of the Bering Strait biomass measurements, which are widely considered the highest in the Arctic.

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Transport and Exchange Across the Fram Strait in 1997-2003—Preliminary Results from the Mooring Arrays

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Since 1997 the volume, heat, and salt transports across the Fram Strait have been measured as a part of the VEINS and ASOF-N projects. Fourteen current meter moorings with additional TS sensors and bottom pressure recorders were deployed at 78°55'N/79°N. Significant interannual changes were found in the structure of the Atlantic water domain. In the eastern Fram Strait two branches of the West Spitsbergen Current were observed, with the main core of the Atlantic water flow over the upper continental slope and a weaker stream shifted offshore. Seasonal signal with maximum northward transport in winter was found in the eastern part of the Strait.

Farther to the west, a width and intensity of the Return Atlantic Current, recirculating Atlantic water in the central Fram Strait, revealed strong variations between analysed years. Volume and heat transports were calculated for the investigated period and values obtained from direct measurements and estimated with use of the linear regression model were compared. Correlations of the observed flows with different atmospheric forcings were also presented, with the highest values found in the eastern part of the Fram Strait.

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Using Airborne Remote Sensing, Coupled with Satellite and Shipboard Data, to Map Changes in Coupled Physical and Biological Processes in the Ocean

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From 2000 to 2002, multiple day and night aerial surveys were conducted using remote sensing tools including lidar, an IR radiometer, MicroSAS, and thermal and digital imagers. Measurements included ocean color, light penetration depth, sea-surface temperature, backscatter from plankton and nekton, and diurnal distributions of foraging sea birds, whales, and sea lions. The study area included fjords, inlets, continental shelves, and open ocean. Temporal variability in physical and biological spatial structure was determined and compared to satellite-derived imagery, bottom topography, and oceanographic results from the companion study.

Over the three-year period, we addressed effects of storms on spatial variability of prey fields for apex predators, spatial variability across the basin in biological standing stocks, effects of ship avoidance on prey fields for apex predators, and the association between surface features (derived from remote sensing) and sub-surface structure. Examples of these results will be shown at the meeting. Developmental progress and future needs for airborne remote sensing of marine ecological processes will also be discussed.

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Airborne Thermal Remote Sensing Surveys of Pacific Walrus *(Odobenus rosmarus divergens)* in the Bering Sea

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The life history of Pacific walrus is tied to the seasonal advance and retreat of sea ice in the Bering and Chukchi Seas. Pack ice floes serve as a resting substrate for walrus groups, and provide greater access to shallow-water feeding areas. Previous aerial surveys of Pacific walrus conducted from 1975–90 used observers to both detect and count walrus groups. The results of these surveys suffered from low precision, and experts have determined that additional visual surveys of this kind would be of little value in monitoring the walrus population.

In April 2002 and April 2003 we conducted field tests using an airborne thermal scanner to detect walrus groups in the pack ice of the Bering Sea. Walrus have considerable thermal contrast from their background environment, and thermal imagery represents one of the best means to locate groups hauled out on ice floes. After visually locating walrus, we first overflew each group at 457–792 m altitude to collect digital photography, and then at altitudes ranging from 792–3,200 m to collect thermal imagery at 1–4 m spatial resolutions. Survey swath widths at these altitudes ranged from 1.5–6 km. Walrus groups were visible in thermal imagery at all resolutions, and there is a significant relationship between the number of walrus in a group and the total amount of heat they produce.

In April 2003 we conducted a pilot survey during which we sampled approximately 30,000 km^2 of sea ice habitat in the Bering Sea. Results of this survey will be used to plan for a range-wide survey of the entire walrus population. Pacific walrus are an important subsistence resource for Native people in both the U.S. and Russia; it will be important to accurately monitor future population trends in relation to changes in sea ice conditions.

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Arctic Marine Ecosystems on Thin Ice: Climatic Influence on Energy Flow and Trophic Structure in the Norwegian Arctic

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Measurements have shown that sea ice in the Arctic has substantially decreased in the past three decades, and models indicate continued trends toward further decreases are likely in the decades to come. Sea ice mediates many of the physical, chemical, and biological processes of arctic marine ecosystems, especially on the shelves where benthic and pelagic systems are extensively coupled. As a result, variations in sea ice can have profound impacts on trophic structure and energy flow.

In a field campaign focused on the northern Svalbard shelf that commenced in spring 2003, we aim to test the hypothesis that changing ice conditions associated with different climatic regimes drive primary production through different carbon sources (ice algae vs. phytoplankton). We propose that such variation in the dominant source pathways of primary production has concomitant effects to both the pelagic and benthic systems, as well as to coupled benthic-pelagic trophic pathways.

The field campaign, combined with laboratory analyses, will test a series of working hypotheses related to the primary producers, zooplankton, and benthic components. We will compare systems influenced predominantly by different water masses, i.e., Atlantic water (warm scenario) vs. arctic water (cold scenario) and we will assess temporal aspects by sampling in different seasons and in different years. Ultimately, this study aims to provide insight into the energetic pathways and trophic structure of this ecosystem and its stability, versus sensitivity in the face of predicted future climate changes.

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North Atlantic Oscillation-Driven Changes to Wave Climate in the Northeast Atlantic and Their Implications for Ferry Services to the Western Isles of Scotland

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Student Poster

The North Atlantic Oscillation (NAO) is the most prominent and recurrent pattern of atmospheric circulation variability over the middle and high latitudes of the Northern Hemisphere. It dictates climate variability from the eastern United States to Siberia and from the Arctic to the subtropical Atlantic. Coincident with a highly positive phase of the NAO Index (NAOI) more active westerlies over northwest Europe have characterized much of the 1980s and 1990s, particularly in winter. Situated on the seaward western edge of northwestern Europe, the Western Isles and northwest coast of Scotland are in close proximity to the westerly tracking, deep Atlantic depressions of the winter months. With most climate models simulating some increase in the winter NAOI in response to increasing concentrations of greenhouse gases, it is likely that the west coast of Scotland will continue to be impacted by North Atlantic cyclones on a regular basis.

The study region is contemporaneously marginal in socio-economic terms and here, more than elsewhere in the UK, ferry services between the mainland and within island groups form vital trade and communication networks linking communities. Associated with the storminess generated by westerly tracking depressions, the seas to the west and north of Scotland are among the roughest in the world during autumn and winter. Consequently, maintaining a reliable ferry service is both difficult and expensive, and while ferry routes avoid the open ocean, some waters are exposed to ocean waves. Here, the inter-annual variability of the ocean wave climate to the west is very high, primarily in response to the NAO, and this sensitivity extends to partially sheltered waters and ferry routes. A deterioration in wave climate in response to either natural variability of the NAO, or as a regional response to anthropogenic climate change is distinctly possible. By analyzing the contemporary response of the wave climate to shifts in the NAO, there is predicted to be a disproportionately large increase in ferry service disruption in response to any deterioration in wave climate. Some of the economic and social implications for this marginal region of the UK are discussed.

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Changes in Sea-Ice Microbial Community Composition During an Arctic Winter

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We hypothesize that microbial communities experiencing similar conditions of environmental extremes will react by altering the species composition of the community in a similar manner. This hypothesis can be tested in sea ice, where microbial communities encased in newly formed sections of the ice at different times during ice growth can be tracked through the winter as they respond to environmental changes. Over the winter, temperatures will decrease dramatically in the ice column (exhibiting a range between -2° and -30° C), causing consequent increases (from seawater salinity to 235 psu) of the brine inclusions—the inhabitable volume of the ice matrix. During the experiment, we expect to find a decrease in the number of common seawater species and an increase in the representation of psychrophilic (and possibly halophilic) species.

Specifically, we will use molecular techniques, including analysis by fluorescence in situ hybridization and terminal restriction fragment length polymorphism, to provide measures of microbial community composition and diversity in discrete sections of first-year sea ice as functions of time, temperature, and other variables. Measurements will be taken weekly at specific temperature horizons over the course of four months between December 2003 and March 2004. Sample collection and laboratory facilities will be aboard the *Amundsen*, the Canadian Coast Guard icebreaker newly renovated for science, while frozen into Franklin Bay, Northwest Territories, Canada.

We predict that temperature (as coupled to salinity) is the driving force behind wintertime changes in the microbial community composition of sea ice; not the availability of light, nutrients, or organic substrates. If confirmed, we can further predict that microbial diversity in sea ice will be affected greatly over the coming decades, as mean annual global temperatures continue to rise and arctic winters presumably grow warmer. Extremophiles that today might benefit from the selective forces of an arctic winter (and benefit society in return, as their genes and enzymes are harnessed for various applications) may be at a distinct disadvantage with only warm, thin ice in the future.

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Progress Toward Understanding Shelf-Basin Interactions: Seasonal Variability in the Oxygen Isotope Composition of Arctic Waters in Conjunction With Other Tracers

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The use of stable oxygen isotope variations in arctic water masses to study temporal mixing processes in surface waters is incompletely resolved because there has been only limited sampling outside of summer. We report here the results of several research sampling programs that are providing data on the isotopic composition of arctic rivers (PARTNERS), shelf and deep-basin regions of the Chukchi and Beaufort Seas (SBI), and flow through the northern Bering Sea and Bering Strait in late winter (Bering Strait Environmental Observatory). Combining these isotope ratio data with other variables, including terrestrial markers, nutrients, salinity, and denitrification indicators provides new insights on the timing and mechanisms of shelf-basin interaction.

Our observations include runoff-influenced waters that remain geographically separated over-winter from well-mixed, brine-influenced shelf and slope waters over the deep Canada Basin. These offshore waters have an apparently different source for persistent lignin in runoff components than waters flowing directly through Bering Strait in the summer.

Also observed were sub-surface ventilation events as brine-injected shelf waters flowed down Barrow Canyon, while in the center of Bering Strait, an increasing sea ice melt signal was advected through Bering Strait in April 2003 as ice melt commenced to the south. These observations of seasonally variable water mixing processes should help inform the SEARCH research planning and provide insights for resolving temporal components of change within the arctic system.

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Change in Fresh Water Inflow from Glaciers and Rivers to the Arctic Ocean

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We have studied the effect of freshwater inflow from the largest pan-arctic rivers and from subpolar glaciers to the Arctic Ocean from 1961 until the end of the 20th century. We have found that discharge data from major river basins do not provide an integrative measure of freshwater inflow to the Arctic Ocean, because only 8% of melt-water runoff from glaciers has been included in the discharge measurements of river runoff over the pan-arctic region. We have evaluated melt-water runoff and net contribution (mass balance) from glaciers to the Arctic Ocean and have compared this with the annual river runoff. River runoff has been calculated as the cumulative departure from the 1961–1990 reference period.

Compare to this reference period the largest contribution from rivers was observed at the end of 1970s, declined in 1980s and began increasing again since the mid-1990s. To the contrary of these the net glacier inflow has showed steadily increases since mid-1960s with the acceleration started at the end of 1980s. Increase in both, glacier melt-water production and net inflow show dominant sensitivity to the increases in air temperature. We attribute the change in river inflow to mostly change in annual precipitation over the 50–70°N latitude belt in North America and Eurasia.

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Hydrochemical Findings from the North Pole Environmental Observatory Program

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The North Pole Environmental Observatory time series began in 2000 to fill in an important gap in our observations of a highly variable and changing arctic ocean-ice-atmosphere system. The distributed components of that observatory are described in detail on the project website: http://psc.apl.washington.edu/northpole/index.html.

Seawater samples have been obtained annually in the spring along various sections in the vicinity of the North Pole for the analysis of a range of chemical tracers. Parameters typically analyzed include salinity, dissolved oxygen, nitrate, nitrite, ammonium, siliceous acid, phosphoric acid, dissolved barium, and oxygen isotopes of water. These samples have been collected from several depths using narrow Niskin bottles in conjunction with CTD profiling. The hydrocasts are conducted through holes drilled in the sea ice at sites reached either by Twin Otter or helicopter. In 2002 and 2003, the CTD also included an SBE-43 new generation dissolved oxygen sensor and high-resolution vertical profiles of this chemical tracer were produced. The chemical data to date can be found at: http://chemoc.coas.oregonstate.edu/users/kfalkner.

In this poster, innovations to assure viable sample collection in the field are outlined. Highlights of the chemical findings are also presented with particular focus on the promise of the dissolved-oxygen sensor. The Arctic Division of the Office of Polar Programs at NSF is thanked for their sponsorship of this hydrochemical program under grant number 9910335, to K. Falkner.

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Highlights of the HLY031 Expedition Hydrographic Program

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This summer marked the inaugural fieldwork of our Canadian Archipelago Throughflow Study entitled "Variability and Forcing of Fluxes through Nares Strait and Jones Sound: A Freshwater Emphasis." Aboard the USCGC *Healy*, our interdisciplinary group sailed from St. John's, Newfoundland, through Baffin Bay and up through Nares Strait to the Lincoln Sea. Along the way we conducted seventy-nine casts of the CTD rosette system to produce detailed hydrographic sections along east-west and north-south trending tracks in northern Baffin Bay, across Smith Sound, southern Kennedy Channel, and northern Robeson Channel.

Casts were made in the heretofore unsampled Petermann Glacier Fiord along its sill and in its deep channel (about 1,000 m) as well as in deep Hall Basin (800 m). Four piston cores that appear to extend to the last glacial were taken off the slope of Bylot Island and a gravity core was taken in deep Hall Basin. Eighteen moorings were deployed in southern Kennedy Channel to monitor current speed and direction as well as temperature, conductivity, and ice draft. Five shallow pressure-sensing moorings were deployed from a small boat with the assistance of divers at sites distributed along and across Nares Strait. Bivalves were also collected at all of these sites for a project aimed at using shell layers to reconstruct chemical conditions in the strait over the past few decades. Hull-mounted ADCP surveys were carried out at several locations including the coastal current near Thule, across Smith Sound, Kennedy Channel, and Robeson Channel.

In addition, the first swath mapping data for the region were collected via the ship's Seabeam system, and underway surface properties via the thermosalinograph system were acquired along the majority of the ship's track. Two teachers posted daily journal entries to our project web page throughout the cruise. A representative of the Nunavut community from Grise Fiord was an active participant in on-board activities. A free-lance professional photographer from Canada also joined us in documenting our science and the environment. The ADCP results are discussed by Muenchow et al. in a companion poster. Highlights from the hydrographic surveys are featured in this poster. To learn more about our project, please consult our website: http://newark.udel.cms.edu/~cats.

We thank the Arctic Division of the Office of Polar Programs at NSF for their sponsorship of this project under the Arctic Freshwater Initiative.

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Recent Arctic Ice Extent Minima Observed with the Sea Ice Index

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In September of 2002, arctic sea ice extent reached a minimum unprecedented in twenty-four years of satellite passive microwave observations, and almost certainly unmatched in fifty years of charting arctic ice (Serreze et al., GRL, 2003). Again, in September 2003, ice retreated to an unusually low extent, almost reaching the previous year's minimum. The Sea Ice Index (http://nsidc.org/data/seaice_index/), a website developed in response to a need for a readily accessible, easy-to-use source of information on sea ice trends and anomalies, assisted in monitoring and diagnosing these extent minima. The NSIDC Near-Real-Time DMSP SSM/I Daily Polar Gridded Sea Ice Concentrations processing stream is used to generate monthly mean, trend, and anomaly images. A Web Image Spreadsheet Tool displays archived images back to 1987 in a tabular format for easy comparison of data from different years.

Sea ice extent anomaly images reveal the distinctive characteristics of the 2002 and 2003 summer minima: ice that has retreated well north of its median extent in the East Siberian and Beaufort sectors, as well as the strikingly anomalous lack of ice off east Greenland. We attribute the shape and position of these summer extent contours to persistent high spring temperatures, enhanced cyclonic conditions in July and August, and smaller than usual ice flux through Fram Strait due to larger than normal SLP differences across the strait. Possibly thinner ice cover preceding summer melt may be a factor as well, and is suggested by negative summertime ice concentration anomalies.

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An Energy Conserving Moored Oceanographic Profiler for Marginal Ice Zone Regions, ICYCLER

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As part of the ASOF-West "Flux through the Arcipelago" project an, ocean water column profiler equipped with a conductivity, temperature, and depth profiler (CTD), fluorometer, buoyancy mechanisms, and internal winch was designed to profile surface-layer water properties for one year under mobile ice cover. The system, called "ICYCLER," is made energy efficient by using the "elevator" concept but using buoyancy instead of gravity as the driving force. The main body (containing the winch and ten times as buoyant as the profiler) moves down 1/10 of the distance while the profiler moves up. Unlike hanging instruments from the ice, this configuration allows measurement to occur throughout the year no matter what the ice conditions are. On a preset schedule, the profiler that carries the CTD is "winched up" to a point just beneath the ice/surface that is defined by an on-board miniature sonar. Then it is immediately "winched down" to safety away from dangerous ice features. The first ICYCLER was deployed in August 2002 in Lancaster Sound in the Canadian Arctic Archipelago as part of the ASOF-West flux project of BIO. A second re-designed ICYCLER with an E-motor is being tested in the Gulf of St. Lawrence for arctic deployment in summer 2004.

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Seasonal, Interannual, and Decadal Variability of the Arctic Perennial Sea Ice

Jean-Claude Gascard Universite Pierre et Marie Curie

In situ observations of sea ice thickness distribution over a large domain of the Arctic Ocean have revealed quite a significant thinning from more than 3 m down to less than 2 m during the past twenty years. Ice extent has shrunk too, but this would correspond to a volume reduction of about 10% compared with 40% due to the thinning.

A second major result from these observations concerns the average thickness of arctic sea ice which would now be less than 2 m compared with an accepted value of about 3 m for the last century. The transition from 3 m to 2 m in the Arctic Ocean is very crucial since it corresponds to a well-defined limit between the perennial (MYI) and the young (FYI) sea ice. Consequently, this raises a very critical issue concerning the eventual disappearance of arctic MYI in the future. Recent observations from satellites equipped with passive and active microwave sensors provided controversial information concerning sea ice in particular for what concern MYI and FYI and there is a strong need for ground truth validation and calibration. Actually models are not really designed for discriminating sea ice types but they could be adapted. It seems the cornerstone concerning the perennial sea ice in the Arctic relies on our capability of measuring sea ice thickness directly from above (free board) and from below (draft) with great accuracy (a few centimeters) over a large domain (basinwide), for a long time (years) and with an ad hoc sampling rate. The 2007 International Polar Year (IPY) and SEARCH could be the right trigger for launching a pilot experiment dedicated to MYI variability observations in the high Arctic using ice-tethered platforms and underwater floats equipped with ULS, together with advanced satellite remote sensing and models educated for discriminating MYI and FYI.

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Achievements and a Potential Role of Underwater Acoustics in Studying Large-Scale Changes in the Arctic Ocean

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The Transarctic Acoustic Propagation experiment in 1994 revealed integral, basin-scale warming of the Atlantic intermediate water layer relative to climatology, which supported the earlier observations of warming in this layer in certain regions of the Arctic Ocean. Both experimental and modeling results have shown that the travel time of individual modes of a low-frequency acoustic signal is a precise indicator of changes in the integral Atlantic water temperature along cross-arctic sections.

The first long-term stationary system of arctic acoustic thermometry was experimentally tested for fourteen months in 1998 and 1999 in the framework of the Arctic Climate Observations Using Underwater Sound program. Remote acoustic observations on the cross-arctic path from Franz Josef Land to the Lincoln Sea detected substantial warming of Atlantic waters and a shoaling of the thermocline that occurred rapidly in the central Nansen Basin (83–84^{0}N, 20–30^{0}E) in the last quarter of 1999. Neither in-situ oceanographic measurements conducted in the adjacent regions in 1998 and later, nor the ocean circulation models, predicted such changes. The long-term acoustic transmissions in 1998–99 were also capable of detecting seasonal variations of the mean thickness of sea ice along the cross-arctic path.

At present, an extensive network of acoustic thermometry paths for multiyear observations in the Arctic Ocean is projected. The feasibility of acoustic halinometry, i.e., remote observations of salinity change in the upper layer, is also examined by numerical modeling.

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From the Shoreline Across the Arctic Shelves: Biological Properties of Sea Ice Ecosystems

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Sea ice is a crucial habitat in polar areas, both in nearshore and offshore waters, and is currently subject to dramatic change with regard to extent and thickness. Recent research has highlighted its significance as a habitat for diverse assemblages of bacteria, protists, and metazoa that drive the ice-associated food chain up to arctic cod and marine mammals. Our research efforts focused on regional characteristics in the abundance, biomass, and diversity of the ice flora and fauna along a gradient from the nearshore, shallow water close to Barrow, Alaska, crossing the shelves of the Chukchi and Beaufort Seas into the deep Canada Basin.

Algal concentration was significantly higher in the sea ice than in the water column both nearshore (max. 330 mg Chl a m^{-3} sea ice, max. 1.6 in 3 m water depth) and on the shelf (max. 1,426 mg Chl a m^{-2} sea ice). Ice algae were characterized by their variable ^{13}C signature (-9.8 to –25.5‰), which varied primarily as a function of biomass. The metazoan community in the coastal fast ice contained a significant fraction of larvae and juveniles of benthic organisms (mainly polychaetes), which were absent farther offshore. Meiofauna abundance in the coastal fast ice showed large seasonal variations, generally following the increase in available algal biomass: Abundances increased from 17,700 animals m^{-2} in Feb 03 to 276,200 m^{-2} in June 03.

At present, no seasonal data are available from the offshore locations, but summer abundances of ice meiofauna in the deep Canadian Basin were low (<11,500 m^{-2}). In conclusion, our data demonstrate large regional variability in the biological characteristics of sea ice, which should be taken into account when discussing recent changes in the Arctic.

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Overview of the Western Arctic Shelf-Basin Interactions (SBI) Project

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Funded through the NSF Arctic System Science (ARCSS) Program and the Office of Naval Research, the Western Arctic Shelf-Basin Interactions (SBI) project began in 1999 (see http://sbi.utk.edu). The goal of the SBI project is to investigate the production, transformation, and fate of carbon at the shelf-slope interface in the Arctic as a prelude to understanding the impacts of a potential warming of the Arctic. An accumulated body of research indicates that climate change will significantly impact the physical and biological linkages between the arctic shelves and adjacent ocean basins. Phase I of SBI used retrospective research and analyses, opportunistic sampling studies, and modeling to prepare for field work in the Chukchi and Beaufort Seas.

The second phase of the SBI project (2002–2006) involves forty Principal Investigators on fourteen integrated projects working in the Bering Strait region and over the outer shelf, shelf break, and upper slope of the Chukchi and Beaufort Seas. Four successful scientific missions to the Arctic in 2002 were completed using three vessels: the USCGC *Healy* for two intensive process cruises in spring and summer, the RV *Alpha Helix* for a mooring cruise in Bering Strait in June, and a July/August mooring deployment cruise on the USCGC *Polar Star*. This interdisciplinary scientific endeavor enlisted up to thirty-nine scientists from nineteen institutions in the U.S., Bermuda, Canada, and Europe during any single cruise, applying a broad array of physical, biogeochemical, and biological measurements.

The 2003 SBI field season included a late-winter helicopter survey (April), mooring turnaround in Bering Strait via the RV *Alpha Helix* (June) and the SBI moorings in the Chukchi and Beaufort Seas via the USCGC *Healy* (Sept–Oct), as well and an intensive hydrographic and sampling survey cruise of all SBI cruise transects using the RV *Nathaniel B. Palmer* (July–Aug). Plans are underway for the final 2004 field season including: a helicopter survey and field sampling project in April, a spring process cruise in May–June, a mooring cruise in June in the Bering Strait, a summer process cruise in July–August, and a mooring retrieval cruise in the Chukchi and Beaufort Seas in September. The four cruises in 2004 are similar to those undertaken in 2002 and will allow inter-annual comparisons of processes in the SBI sampling region. Phase II of SBI will continue through 2006 with data synthesis. The final chapter of SBI (Phase III, 2007–2009) will focus on using the new understanding of this productive arctic ecosystem to model and develop scenarios of the potential impacts of climate change on shelf-basin interactions.

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Reconstructing Marine Resource Usage and Trophic Dynamics at Mink Island Site (XMK-030)

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Student Poster

The stable isotope signatures of marine vertebrates and seabirds recovered from this archaeological site offer excellent data on past environmental and ecological conditions over a 7,000-year period. Alaska coastal sites contain well-preserved archaeofauna and abundant deposits of marine shellfish. Ocean productivity is recorded in the organic carbon content preserved in marine and freshwater sediments as well as in the organic matrix of marine vertebrate remains. Stable carbon and nitrogen isotopes ($d^{13}C$ and $d^{15}N$) derived from bone collagen provide information about changes in food web dynamics, productivity levels, and thus, ecosystem changes. Any changes in the length of the marine food web induced by climate change or food web interactions will be exhibited in the $d^{15}N$ in the bone collagen of marine vertebrates. Changes in marine resource abundance are reconstructed from calculation of relative abundances of marine species in archaeological and other sedimentary deposits. The changes are, in turn, related to perturbations in the natural system.

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Sea Ice Thickness Measurements by a Low-Frequency Wideband Penetrating Radar

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The thickness of sea ice is an indicator of the state of ocean circulation and associated air-sea heat exchange within the polar regions, which can have profound impacts on global heat balance and ocean thermohaline circulation. Synoptic and direct measurements of sea ice thickness by remote sensing techniques have proved elusive, with limitations in measurable thickness range or spatial and temporal coverage.

A prototype low-frequency wideband penetrating radar for measuring sea ice thickness was designed and successfully tested at Barrow in May 2003. Electromagnetic modeling and simulations of the complex and lossy sea ice were performed to determine the appropriate radar frequencies needed to penetrate the entire sea ice volume. Based on the simulation results, a prototype radar system was built that included a VHF (50–250 MHz) radar system for measuring thick (1–8 m) arctic sea ice and a UHF (300-1300 MHz) radar system for measuring thin (0.5–2 m) ice in the Arctic and the Antarctic. The field test indicated that the VHF component was sensitive to ice thickness which ranged from 0.5–4 m. In situ measurements of thickness by an EMI and augers were obtained for validation. This study will present comparisons of the radar and in situ measurements and outline challenges associated with measuring ice thickness with VHF radar, with an emphasis on key properties of the snow-ice medium that impact the ability of a radar to characterize the ice thickness.

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A New Look At Arctic Polynyas with Multi-Sensor Satellite Data

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In this study we seek to examine the variability of Northern Hemisphere polynyas and their response to recent large-scale atmospheric patterns. Recent climate changes, starting with the large 1989 shift in the Arctic Oscillation (AO), have strongly affected the ice circulation and export in the Arctic Ocean. It appears likely that polynya activity, and thus their possible role in the variability in the arctic halocline, may be directly related to these significant shifts in atmospheric circulation. However, no recent large-scale remote sensing assessment of arctic polynya activity has been performed during this dynamic period. We have developed a unique approach to detect ice thickness and heat flux within polynyas using a combination of satellite sensors. We are beginning now to apply the technique to time series, first over the Alaskan coastal region and then to the greater Arctic.

This paper describes our multi-sensor approach which combines passive microwave data from SSM/I, AVHRR imagery, SAR imagery from RADARSAT, and scatterometer data from QuikScat. This initial suite of instruments captures the polynya opening and closing and permits tracking of the areas of thin ice formation over time. We start with a validated algorithm for thin ice thickness up to 20 cm and heat flux developed previously using AVHRR. We have found that SSM/I 37 GHz polarization ratio V/H is also sensitive to this same range of thickness, which enables a daily estimate of polynya activity. We will discuss time series results from the large polynya activity off the Alaskan coast with estimates of salt flux and compare these results to published model estimates and measured changes in the Arctic halocline.

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Bering Ecosystem Study Program (BEST)

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We present information on a new research program being planned for the eastern Bering Sea, the Bering Ecosystem Study Program (BEST). In recent decades, components of eastern Bering Sea marine ecosystems have shown unexpected changes in abundance or distribution that, in many cases, correlate with climate-associated physical variability. Thus, the overarching question to be addressed in BEST is: How will climate change affect the ecosystems of the Bering Sea? It is important to resolve this question because the eastern Bering Sea supports stocks of commercial fish that generate more than 40% of all the United States' fish and shellfish landings, is directly or indirectly the source of over 25 million pounds of subsistence foods used by nearly 55,000 Alaska residents, and is home to vast numbers of marine birds and mammals. Understanding the underlying processes responsible for ecosystem responses to climate variability is essential for providing good stewardship and effective management of sustainable human exploitation of the Bering Sea's riches.

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Sub-diurnal Mesoscale Sea Ice Deformation in the Spring Beaufort Sea Seasonal Ice Zone and Its Influence on the Sea Ice Mass Balance

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We report the findings from a mesoscale ice deformation experiment performed at the ONR ICEX ice camp in the Beaufort Sea, 73ºN 146ºW, March 26 to April 27, 2003. The camp was at the edge of the multi-year pack north of Prudhoe Bay. On March 26 a lead opened close to the camp, and this lead was monitored continuously for three weeks. GPS receivers were placed in an array around the lead, and position recorded every ten seconds. The deformation and strain rate are calculated and compared to personal airborne observations of larger-scale deformation features in the coastal shear zone.

The sub-diurnal features of the lead scale deformation are investigated and analyzed in relation to synoptic scale forcing of the ice pack. The lead is found to have a twelve-hour and twenty-four-hour cycle in divergence and shear. The character of the deformation is remarkably different between periods of sustained high and low pressure weather systems (identified from NCAR/NCEP reanalysis and personal weather log). It is found that during low pressure the lead deformation is characterized by diurnal closing and opening, with a little shearing and periodic ridge building. In contrast, high pressure periods are characterized by diurnal opening and closing in concert with large shearing events. From analysis of SAR images we find the synoptic time scale deformation in the coastal shear zone follows that observed at the ICEX lead. The volume of new ice produced and ridged in the ICEX lead is estimated, indicating the magnitude of ice mass produced due to tidal and inertial forcing in the Beaufort Sea seasonal ice zone. The dependence of the new ice production on the regional scale wind forcing is investigated, indicating greater ice production during atmospheric highs, predominately through inertial motion. Our results show that to simulate global sea ice mass it is important to use a constitutive relation and oriented thickness distribution that represents observed lead scale deformation, and that inertial and tidal forcing should be included. Toward this goal, more field data of mesoscale deformation are required.

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Spatial Variations in Sea Ice Habitats, Marine Mammals, and Food Resources

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Changes in sea ice conditions in the Bering and Chukchi Seas affect ice-inhabiting seals and walruses directly by altering the availability of suitable substrate used for resting, molting, and giving birth, and indirectly by altering pelagic and benthic production. Regional shifts in population density would be expected to vary among species because they are distributed variously among ice types and tend to partition food resources. In turn, food web dynamics may be regionally impacted by shifts in these population densities.

For example, the Pacific walrus *(Odobenus rosmarus divergens)* plays a prominent role in the arctic marine ecosystem. They modify the seafloor by tilling large quantities of surficial sediment while rooting for benthic invertebrates, each year resuspending more than nineteen times the annual sediment discharge of the Yukon River. While doing so, they remove as much as three million mt of biomass from the benthos each year, equivalent to 170 times the total annual goundfish landing in Alaska.

Walruses mainly occupy a narrow band of the ice edge in the Chukchi Sea in summer, and divergence zones and polynyas throughout the range of sea ice in the Bering Sea in winter and spring. During years of extreme northern retreat of the pack ice in the Chukchi Sea, toward deeper waters of the Arctic Basin, walruses lose access to their preferred foraging areas over the shallow continental shelf near the ice front and are forced to occupy land haulouts. Similarly, during years of minimal ice extent in the Bering Sea, they lose access to southern regions of the shelf. As a result, their influence on benthic processes from foraging are likely to shift over substantial areas.

Studies that examine the persistence of various ice habitats and their significance to pelagic and benthic production and marine mammal distributions, and interactions between marine mammals and their prey should enable better predictions of the potential impacts of global warming to arctic systems.

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Distribution of the Convective Lower Halocline Water in the Eastern Arctic Ocean

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We investigate distribution of Convective Lower Halocline water (CLHW) in the eastern Arctic Ocean using observational data. At first, results from ice-drifting buoys showed differences of water mass characteristics in the upper ocean in the Amundsen Basin, over the Arctic Mid-Ocean Ridge, and in the Nansen Basin. The CLHW, which is represented as salty water with freezing temperature, covers the Arctic Mid-Ocean Ridge and the Nansen Basin, but the property of CLHW in the Amundsen Basin has been weakened in the early 2000s. The differences of water mass characteristics among these regions were caused by whether effective winter convection occurred in the basin or not.

Using the climatological data, we found that typical CLHW covers only the Nansen Basin. The advance/retreat of CLHW since the 1990s in the eastern Arctic Ocean was investigated using historical observational data. In the early 1990s, the CLHW covered only the Nansen Basin, which is similar to the result from the climatology. The area of the CLHW extended to the northern side of the Arctic Mid-Ocean Ridge in the mid 1990s, and moreover, the CLHW covered the whole of the Amundsen Basin in the late 1990s. In the early 2000s, the area of CLHW shrank and moved back to the northern side of the Arctic Mid-Ocean Ridge. These results correspond to the results on the surface salinization in the eastern Arctic Ocean.

It should be concluded that the change of cold halocline was caused not only by a change of surface salinity but also by a frontal shift of the whole of the upper ocean in the eastern Arctic Ocean. Accurate ocean current measurement has been conducted

using ice-drifting buoys. We found that topographic-controlled current was dominant over the Lomonosov Ridge and the Arctic Mid-Ocean Ridge. In the Amundsen Basin, mean current direction was from the Lomonosov Ridge to the Arctic Mid-Ocean Ridge in the spring to early summer season. The mean speed is about 2.0 cm/sec. This result is different from the notion that was imaged from sea-ice drift, and suggested that there would be along-isobath difference of water properties within the Amundsen Basin.

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Sub-Daily Sea Ice Motion and Deformation from RADARSAT Observations

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We find a persistent level of oscillatory sea ice motion and deformation, superimposed on the large-scale wind-driven field, in mid-winter (February 2003) and spring (May 2002) in the high Arctic over a 200-km region centered ~(85°N, 135°W). At this latitude, the RADARSAT wide-swath SAR coverage provides 4–5 sequential observations every day at a sampling frequency near the orbital period of ~101 minutes. Ice motion is derived from the acquired SAR imagery. Periodic correlations in ice motion and deformation can be seen in length scales from 10 km and above, and suggest a twelve-hr oscillation that is more likely associated with the inertial rather than tidal frequencies. Divergence/convergence of ~10–7/s or ~0.1–0.2% peak-to-peak is seen in both data sets, with the mid-winter data set having smaller values. These observations are remarkable in that short-period ice motion was previously believed to be inhibited by the strength of the ice pack in the high Arctic during winter. New ice production due to the recurrent openings and closings at these temporal scales, even though small, could be significant within the winter pack.

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Annual Cycles of Multi-year Sea Ice Coverage of the Arctic Ocean: 1999–2003

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For the years 1999–2003, we construct the annual cycles of multi-year (including second year) ice coverage within the Arctic Ocean using the fields of QuikSCAT and RADARSAT backscatter, and records of ice export from satellite passive microwave observations. Between December and May, the time series of multiyear (MY) coverage is derived from the active microwave datasets. For the balance of the year, the coverage is extended using a simple area balance procedure based on area export and deformation. The uncertainties in the estimates are higher in the latter case. Ice export reduces the MY ice coverage over the winter.

At the beginning of each calendar year, the coverage of MY ice is: 3,744 ± 103 km^2 (2000), 3,834 ± 103 km^2 (2001), 4,293 ± 103 km^2 (2002), and 4,016 ± 103 km^2 (2003). In the mean, MY sea ice covers ~60% of the Arctic Ocean. From the annual cycles, the first-year (FY) ice areas that survive the intervening summers are: 1,065 ± 103 km^2 (2000), 1,295 ± 103 km^2 (2001), and 396 ± 103 km^2 (2002). The MY coverage in 2003 was not reduced significantly following the record minimum in arctic sea ice area in the summer of 2002; the effect is actually seen in the lowest area of surviving FY ice over the three summers. The estimated MY coverage compares reasonably well with the minimums in summer sea ice coverage from passive microwave observations. The discrepancies are discussed.

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Narwhal Pack-Ice Habitat: Increasing Threats?

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Narwhals *(Monodon monoceros)* are among the most conspicuous of all cetaceans inhabiting dense arctic pack ice and offer a unique opportunity for examining responses to anthropogenic and global warming-induced impacts in offshore areas. Narwhals make extensive annual migrations from high-arctic summering grounds to wintering grounds occupied between November and April in central Baffin Bay and North Davis Strait. Intense feeding behavior has been documented during winter based on stomach content studies, reduced Greenland halibut *(Reinhardtius hippoglossoides)* densities, and skewed halibut length frequencies in areas with whales. This suggests a major portion of the annual energy intake for narwhals in high-arctic Canada and West Greenland is obtained in Baffin Bay in winter.

Imminent expansion of an offshore commercial fishery for Greenland halibut threatens narwhal feeding efficiency and overall fitness. Sea ice concentrations on wintering grounds average 97% and less than 3% open water is available between January 15 and April 15. Decreasing trends in the area of open water during the period of maximum month of ice cover have been found on wintering grounds, significantly so in northern Baffin Bay (-0.04% per year, SE 0.02). At the same time, inter-annual variability in the fraction of open water is significantly increasing at +0.03% per year (SE 0.006), leaving few options for narwhals to detect increasing ice trends in their habitat. Due to high site fidelity, complete coverage of the wintering grounds could lead to mass mortality of narwhals, as observed by ice entrapments in coastal areas. Understanding narwhal spatial habitat use patterns will lead to identifying regions that can be considered critical habitat, minimizing effects of anthropogenic factors, and predicting responses to climate change in the high Arctic.

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Vertical Export of Particulate Organic Carbon and Calibration of Sediment Traps Using ^{234}Th in the Barents Sea

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Student Poster

^{234}Thorium ($t_{1/2}$= 24.1 days) is a key tracer for determining the vertical export of particulate organic carbon (POC), which can be calculated from the ^{234}Th deficit and the POC/^{234}Th ratio of sinking particulate matter. Samples for ^{234}Th and POC measurements were collected at four stations during the CABANERA cruise from July 8–22, 2003, along a north-south transect in the Barents Sea. Dissolved ^{234}Th in seawater was measured at five depths at each station (10, 20, 60, 90, 120 m), while particulate ^{234}Th and POC were measured at three of these depths (20, 60, 120 m). Particulate ^{234}Th and POC were measured at the same three depths in the drifting sediment traps for the calibration of the traps.

Total ^{234}Th activities were close to ^{238}U activity, which indicates that there is no major ^{234}Th/^{238}U disequilibrium. At 60 m, the ^{234}Th fluxes varied from 410.4 to 495.4 dpm/m^{-2}/day^{-1}, and are slightly lower in arctic water than in Atlantic water. Ongoing work (POC determinations) will lead to determination of the export fluxes of POC in both seawater and sediment traps.

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Arctic Sea Ice Variations and Relations to Atmospheric Forcing

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High-latitude atmospheric circulation and the interaction between the atmosphere, sea ice, and ocean are the key processes controlling the climate in the polar areas, and, extend reflections up to sub-polar regions. In a project AICSEX (Arctic Ice Cover Simulation Experiment) by the EC we studied the time development of the sea ice variations in the Arctic and in the Baltic Sea, and their relations to large-scale atmospheric forcing.

The arctic sea ice extent and concentration over the last decades (1978 onwards) were studied using the HadISST1 (Hadley Centre, Met Office, UK) data especially. The decreasing trend of the summertime ice extent, reported in the literature, was not continued from 1996 to 2002, and in this light, the current development remains open. Additionally, comparisons of the ice extent and areas of low ice concentration with those of high concentration (compact, over 97%) indicate mutually different time development during the last decades. The large-scale atmospheric forcing, the Arctic Oscillation (AO), was found to correlate with the total sea ice extent and areas of low ice concentration, but also with the area of high-concentration sea ice. However, the correlation was negative with the former and positive with the latter. Trends toward high ice concentration were the most significant in the Greenland Sea, along the Canadian Coast and the Chukchi Sea, all coastal regions away from the central Arctic. This is consistent with the view, in which increased cyclonic atmospheric forcing causes divergence of the central arctic ice field further converging at the boundaries, thus affecting the freshwater balance of the basin.

In the Baltic Sea, the sea ice climate was found to be to a high degree dependent on the northern Atlantic forcing, in practice characterized in terms NAO. Accordingly, sea ice extent, length of the ice season, as well as the ice thickness, correlate and have a causal relationship with the wintertime NAO. After fifteen years of mild ice winters, the last ice winter, 2002–03 was moderate, or even severe from the point of view of winter navigation.

Unfortunately, CGCM models cannot predict AO or its discrete paradigm NAO, and neither, can they link AO and NAO undoubtedly with climate change. Therefore, one cannot justify how much sea ice variations found might come from the global warming and climate change.

Finally, a study in progress on comparison of the arctic sea ice variations and anomalies with those in the Antarctic indicate interesting counter-phase similarities, suggesting global meridional trans-connections even up to both polar regions.

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Modeling Ice Algae Growth and Decay in Seasonally Ice-Covered Regions of the Arctic Ocean

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Student Poster

Although ice algae are estimated to represent less than 25% of the total primary production in the Arctic Ocean they would be exported to depth more efficiently than pelagic phytoplankton. The timing of ice algae export from the surface layer, which lowers the CO_2 partial pressure of the ocean's surface, would also be important since it occurs just before the melting of the ice cover, thus reducing or suppressing CO_2 outgassing when the ocean's surface is first exposed to the atmosphere.

The importance of ice algae for carbon cycling could also increase with climate change since their abundance is higher in first-year ice, the extent of which could increase with the predicted decrease in multi-year ice. Snow thickness appears to control the onset and decline of the ice algae bloom through its control on the amount of solar radiation that reaches the algae. On the other hand, the rate of ice growth at the ice bottom plays an important role on the ice skeletal layer structure, where ice algae are found. We here explore the effects of these physical forcings on the onset, variability, and decline of an ice algae bloom, using a coupled snow-ice-ice algae model. The latter is part of a more complete ice-ocean ecosystem model that will be used to study carbon cycling on Arctic Ocean shelves, the relative importance of the solubility and biological pumps, and how these processes could be affected by climate change.

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Variability of Sea Ice Thickness and Thickness Changes in the Arctic

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Model calculations of pack ice mean thickness and estimates of its monthly changes due to advective and thermodynamic effects are presented. The model is a coupled ice/ocean model driven with NCEP/NCAR Reanalysis daily air pressure and air temperature fields. The model has ice thickness, enthalpy, and snow depth distributions and has a grid size of 40 km. It includes assimilation of ice extent and ice velocity measurements. The net change in the ice thickness is the sum of the changes due to advection and thermodynamic processes. Means, variability, trends, and principal components of the thickness and thickness changes are presented for each of the four seasons. The relationships of the thickness changes with the Arctic Oscillation and Pacific Decadal Oscillation are also presented.

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Palynological Evidence for Holocene Climate Variability in the Laptev and Kara Seas (Eurasian Arctic)

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Despite a growing interest in the paleoclimate evolution of the Holocene period in the Siberian sector of the Arctic Ocean, relatively few data are available from marine records of the shallow Siberian shelf seas. Within the frame of the joint Russian-German projects “Geosystem Laptev Sea” and “Siberian River Run-off (SIRRO),” high-resolution records from the Kara and Laptev Seas have been studied for their palynological contents in order to reconstruct sea-surface conditions and freshwater input from the large Siberian rivers during the Holocene.

Holocene dinoflagellate cyst assemblages from both the Kara and Laptev Seas indicate the presence of a marine thermal optimum in the early Holocene. The onset occurred in the Laptev Sea shortly after the transition to the Holocene, though sediment cores studied so far from the inner Kara Sea do not span this period. A long-term cooling in the mid and late Holocene is recognized in both shelf seas, but major steps obviously did not occur synchronously. The records are characterized by few sub-millennia oscillations, suggesting that conditions were relatively stable in the later part of the Holocene. Chlorococcalean algae reflect a variable freshwater input during the Holocene that was related to the post-glacial sea-level rise and retreat of the estuaries of the large rivers, the Ob, Yenisei, and Lena, to their present positions.

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AOOS: The Alaska Ocean Observing System

Molly McCammon Alaska Ocean Observing System

The Alaska Ocean Observing System is part of a growing national network of integrated ocean observing systems that will improve our ability to rapidly detect changes in marine ecosystems and living resources, and predict future changes and their consequences for the public good.

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Observations from the Canada Basin: 1997–2003

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Canada Basin waters are in transition, responding to the effects of upstream change in atmospheric and oceanic circulation. The Canada Basin is unique in that it receives inflow from the Pacific Ocean, via the Bering/Chukchi Sea, and the Atlantic Ocean, which enters from the Makarov Basin via Fram Strait and the Barents Sea and the Nansen and Amundsen Basins. Observations made during SHEBA/JOIS in 1997-98 and on cross-basin JWACS surveys in 2002 and 2003 showed that Canada Basin waters, and in particular the composition of the halocline, can no longer be viewed as laterally homogeneous and in steady state.

In 1997–98 the halocline was thinner over the Mendeleyev Abyssal Plain and northern Chukchi Plateau. Here, Pacific-origin upper and middle halocline waters occupied the upper 80 m of the water column and underlying Atlantic-origin lower halocline waters were fresher, colder, and much more ventilated than observed in the past. These new observations of a sub-surface oxygen maximum suggest that outflow from the East Siberian Sea now supplies the Canada Basin lower halocline. East of the Northwind Ridge the halocline was thicker and appeared relatively unchanged.

Comparisons will be made with data collected in 2002 and 2003. Nutrients, temperature, and oxygen are used to identify spreading pathways of Pacific and Atlantic-origin waters. Time series data follow the advance of warmer Atlantic-origin waters over the Chukchi Gap and into the southern Canada Basin, signaling the arrival of warm-anomaly Fram Strait Branch waters, first observed upstream in the Nansen Basin in 1990.

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Changes in Arctic Productivity: Is It Ice?

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Has the carrying capacity of the western Arctic and Bering Sea declined? Using stable carbon isotope data from the baleen of bowhead whales as a proxy for food web productivity, Schell (2000) has argued that a drop of 30% to 40% has occurred over the past five decades. While this contention is not without challenge (e.g., Cullen et al., 2001) this remains as the accepted paradigm to account for ecological changes in the region. However, McRoy et al. (2001), using seasonal nutrient depletions on the Bering Sea shelf for the past twenty years, found no such trend in primary productivity. We measured the stable carbon isotope signatures of phytoplankton and sea ice algae in the Beaufort Sea to construct a food-web mixing model with these two primary sources of carbon. The model estimates the proportion of sea ice algal carbon in the diet of the whales. Estimates range from greater than 30% to about 10% since 1945. A strong relationship exists between this trend and the extent of summer sea ice, suggesting that the decline in the whale baleen isotope values is related to a shift from ice algal to phytoplankton carbon.

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Submarine Melting at Temperate Tidewater Glacier Termini: How Significant Is It?

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One of the most important unresolved questions concerning temperate tidewater glaciers is the role that submarine melting and proglacial convection play in controlling terminus stability. Little is known about ocean thermal forcing of temperate tidewater glaciers even though its seasonal and long-term variation may significantly influence calving speed, terminus dynamics, and ocean convection. Relationships developed from field, experimental, and analytical studies on icebergs' drifting and melting in seawater have been used to estimate submarine melting at calving termini. However, these calculations give estimates that are typically a small fraction of total calving rate.

Recently, Motyka et al. (2003) used heat and mass balance analysis based on glacier and fjord measurements at LeConte Glacier, a tidewater glacier in southeast Alaska that terminates in 250-m-deep water, to estimate submarine melting. They found that proglacial convection was substantial and that submarine melting contributed significantly to ice loss at the terminus during late summer. Melting was at least as significant as calving in controlling terminus position—if not more. In a similar study at Columbia Glacier, Walters et al. (1988) also found that melting there was seasonally significant, with melt being about half the iceberg calving flux during the summer. These field studies indicate that iceberg analogies do not accurately reflect the dynamic process of turbulent convective flow along the terminus face that is driven by discharge of buoyant subglacial and englacial water.

In our model we propose that turbulent upwelling of subglacial freshwater draws in warm ocean waters and that the mixture rises along the submarine face and melts ice. A consequence of this model is that submarine melt rates should vary as a function of ocean water temperature and subglacial discharge. We suggest that seasonal fluctuations in the terminus position of tidewater glaciers are directly related to seasonal changes in submarine melting, much as termini of land-terminating glaciers are affected by seasonal changes in surface ablation.

Submarine melting may also be involved in controlling the long-term stability of tidewater glacier termini through direct oceanic thermal forcing. Submarine melting could help explain the correlation between annual "calving speed" and water depth found for many well-grounded tidewater glaciers. This is because the percentage area of the terminus face exposed to submarine melting would increase as a function of water depth. It has also been noted that the calving speed-water depth correlation only holds when annually averaged values are used and breaks down for shorter time periods. Our model is consistent with this observation as seasonal changes in convective flow and seawater temperatures would significantly affect melt rates but annual melt rates should be approximately the same.

Buoyancy-driven submarine ablation and seawater temperatures could also help explain the order-of-magnitude disparity in "calving speeds" between tidewater and lacustrine settings. The lack of a strong density contrast and the generally cooler water temperatures encountered at lacustrine calving glaciers would inhibit convection and melting at a sublacustrine face in contrast to submarine environments.

Lastly, there may be a spectrum of submarine melting regimes, from polar ice shelves with little subglacial discharge (e.g., Pine Island, Antarctica) to those with significant subglacial discharge (e.g., Jakobshavn, Greenland) to temperate tidewater glaciers with no floating tongue and strong seasonal subglacial discharge.

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Basin-Scale Arctic Ocean Transient Tracer Data Sets

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Beginning in about 1987 an international effort has been mounted to gather a baseline of Arctic Ocean hydrography. The LDEO Environmental Tracers Laboratory has participated in the collection, measurement, and analysis of samples for measurement of the tracers $^{16}O/^{18}O$, $^{3}H/^{3}He$, ^{14}C, $^{39}Ar/^{40}Ar$, and CFCs. These tracers yield information on water mass transformations and transit times that cannot be derived from salinity and heat content by themselves. They have been very useful in documenting the changes that are the subject of the oceanic component of SEARCH. We have started to merge the tracer data from many cruises into a single, quality-controlled database.

In this poster, we exhibit some of the most interesting features of the basin-wide data, including: spreading rates for Atlantic-derived boundary currents from "age" tracers; laterally extensive lenses of relatively old water at the base of the halocline; apparent regions of upwelling on the southern flank of the Mendeleyev Ridge, and a sharp discontinuity in diapycnal mixing that correlates to bathymetry, but not to any apparent density structure.

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Arctic Changes Observed with Scatterometer Products

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Recent observations indicate that arctic regions are undergoing significant changes. In 2002, sea ice extent shows a record minimum, and surface-melt area over the Greenland ice sheet set a record maximum (Sturm et al., Meltdown in the North, *Sci. Amer.*, 2003; Perovich et al., Assessing, understanding, and conveying the state of the arctic sea ice cover, AGU Fall Meeting, 2003). To observe polar changes, we develop new and/or improved geophysical products from satellite scatterometer data with a frequent coverage (two times per day) over large scales.

Although new compared with other satellite data sets, scatterometer data have been collected by SeaWinds on the QuikSCAT Satellite into the fifth year since its launch in 1999. Together with the follow-on SeaWinds on the Midori-II Satellite launched last December, a decade of scatterometer data is expected. We have developed and implemented the concept of "satellite stations," at which time series satellite data are collected around special locations such as field experiment sites, weather network stations, data buoys, and instrumented sites. Combined with in situ measurements at these stations, satellite data can be appropriately interpreted to derive geophysical products, and conversely the satellite time series extend the observations over time at the stations. Geophysical products that we derive from scatterometer data include sea ice extent over all seasons, sea ice types including seasonal and perennial ice extent, polynya area, melt onset and freeze-up dates, numbers of melting and freezing days, melting and refreezing zones over ice, duration of melting and freezing seasons, and wind field up to the vicinity of the sea ice edge.

For the first time, our observations at Chuckchi Satellite Station (Perovich's field site) and C-ICE Satellite Station (Barber's field site) consistently reveal the longest melting season in 2002 followed by the shortest freezing season since the beginning of the QuikSCAT data set. Large-scale geophysical products obtained from QuikSCAT data extend the observation over the entire Arctic Basin. These results will help to understand the peculiar record of the cryospheric conditions in 2002. Such observations over long term are important to monitor changes in polar regions.

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An Ecopath Model of the Arctic Ocean: The Time Is Ripe

Thomas A. Okey University of British Columbia

Student Poster

The latest generation of Ecopath models are non-steady-state descriptions of the trophic flows throughout a defined ecosystem (and time period) using biomass, nutrient, or energy units. These models are constructed under mass-continuity constraints and are used to describe the structure and characteristics of a system's food web and to provide a framework and synthesis for learning about whole communities and their respective parts.

Dynamic routines within the (free) Ecopath with Ecosim software allow explorations of the direct and indirect effects of environmental changes, fisheries, pollution, or combinations thereof on the system's biological community and its various components. It now contains tools for distinguishing the relative strength of the various forces shaping these communities. Construction of an Ecopath model of the Arctic Ocean would provide an integrated ecological baseline, an accessible and transparent view of the biological community on a broad scale, and a useful framework for future research and policy planning.

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Sunlight Removal of CDOM from the Mackenzie River: Implications for Ocean Color in the Beaufort Sea

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As part of the CASES program (http://www.giroq.ulaval.ca/cases/), we are investigating the influence of the Mackenzie River plume on coastal ocean optical properties in the Beaufort Sea. In particular, we are investigating the transport of colored, or chromophoric, dissolved organic matter (CDOM), which strongly attenuates UV and PAR in natural waters.

In October through November 2002, several samples were collected from upriver, at the river mouth, and along a transect extending offshore, for the following optical measurements of CDOM: dissolved absorptivity (aCDOM), synchronous fluorescence (SF), excitation-emission matrix fluorescence (EEM), and dissolved organic carbon (DOC). These measurements quantitatively and qualitatively characterize DOM in natural waters.

In general, we observed a decrease in aCDOM from the riverine to offshore samples. Spectral slopes indicate a preferential loss of UV-A absorptivity that was supported by SF spectra, which showed a loss of humic and fulvic moieties and predominance of a one-ring aromatic peak indicative of aromatic amino acids.

In a three-day sunlight exposure experiment designed to simulate the photochemical degradation of CDOM, we observed very fast rates of decrease in aCDOM and SF. In fact, the SF spectra began to emulate offshore SF spectra of Beaufort Sea water. The aCDOM decreased by 13%, 9%, and 5% each day. DOC did not decrease significantly from the initial value until the third day of exposure where we observed a 5% loss of DOC, presumably as CO_2. We will also present results of spectral weighting function calculations used to compare the relative photoreactivity of riverine and marine waters in this region.

Our findings suggest that photochemical degradation strongly affects the optical properties of Mackenzie River water entering the Beaufort Sea. We further suggest that the 5% conversion of DOC to CO_2 places an upper limit on the short-term sunlight removal of DOC from surface waters in the Western Canadian Arctic.

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Changes in the Overflow Through the Faroe Bank Channel

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The Faroe Bank Channel (FBC) is the deepest passage across the Greenland-Scotland Ridge, which separates the Arctic Ocean and Nordic Seas from the North Atlantic. Through the depths of the channel there is a continuous flow of cold, dense water, which contributes about one third of the total dense overflow across the Ridge. Previous investigations have indicated a reduction in the FBC-overflow through the second half of the 20^{th} century, with accelerated reduction toward the end of the period. Here, we present new results of ongoing measurements from the channel, including direct current measurements as well as measurements of water mass properties. From these, we discuss trends in volume flux of overflow waters with different characteristics.

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Sea Ice Velocity in the Fram Strait Monitored by Moored Instruments

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The Fram Strait sea ice velocity was measured by means of a new method using moored Doppler Current Meters in the period 1996–2000. Almost three years of ice velocity observations near 79°N 5°W are analyzed. The average southward ice velocity was 0.16 m/s. The correlation between the ice velocity and the cross-strait sea level pressure (SLP) difference was R = 0.76 for daily means and R = 0.79 for monthly means. The same cross-strait SLP difference exhibits a positive trend since 1950 of 10% of the mean per decade. By a simple linear model, we compute mean sea ice area flux to 850,000 km^2/year for the period 1950–2000. Ice thickness, monitored by means of Upward Looking Sonars since 1990, is also discussed. The combined data gave a monthly ice volume flux of 200 km^3 during the last decade, with no significant trend.

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Sea Ice Mass Balance Measurements: Insights and Inferences

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General circulation models indicate that arctic sea ice may be a sensitive indicator of climate change. Accordingly, efforts are underway to improve and expand observing systems designed to monitor changes in the arctic sea ice cover. The mass balance of the ice cover is an important component of such observing systems, since it is an integrator of both the surface heat budget and the ocean heat flux. Satellites provide information on ice extent, as well as the onset of melt and freezeup, and submarine surveys furnish large-scale information on changes in ice thickness. However, neither method delineates potential sources of observed changes: e.g., differences in surface heat budget, variations in ocean heat flux, or modifications due to ice deformation. Ice mass balance data provide this critical insight.

In spite of the importance of the ice mass balance, there is a paucity of data. The available observations indicate that there is significant spatial and inter-annual variability in the mass balance. There are considerable differences in ice growth, as well as the relative amounts of surface and bottom ablation. Drifting and shore-based manned stations are valuable sources of mass balance data, but are logistically demanding and limited in areal and temporal extent. Station data can be supplemented with autonomous ice mass balance buoys to create a coordinated network of mass balance observing sites. Mass balance data from these sites can be assimilated with other direct and remote sensing data and sea ice models, to provide an estimate of large-scale ice mass balance.

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Quantitative Importance of Macrofauna: A Test of Sieve Mesh Size Biases on Sampling in a High Benthic Biomass Area

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Student Poster

The effects of sieve mesh size on estimates of standing stocks of benthic populations was examined on the continental shelf of the Bering and Chukchi Seas, an area with high benthic biomass. Benthic grab samples were collected on a 1.0 mm mesh, and materials passing through that screen were collected on 0.5 mm mesh. Collections were made at 16 stations occupied on the CCGS *Sir Wilfrid Laurier* in July 2003 during an annual cruise associated with the Bering Strait Environmental Observatory in both the Bering and Chukchi Seas.

Results indicate that both mesh sizes retain similar percentage ranges of total individuals at each station, 30–80% for 0.5 mm mesh and 20–70% for 1.0 mm mesh, when compared with combined abundances of both mesh sizes. The total mass collected on the larger 1.0 mm screen ranged from 95% to 99% of all biomass collected on both screens; the remaining wet biomass collected on the 0.5 mm mesh ranged from 0.5% to 2.0% of total biomass on both screens. We are currently evaluating differences in benthic faunal diversity for the two screen sizes using the Shannon-Weaver diversity index. It appears, however, that sampling with a 1.0 mm mesh is a small enough sieve size to adequately estimate benthic biomass on the continental shelves of the Bering and Chukchi Seas and that the macrozoobenthos lost through this sieve size is a relatively small percentage of total biomass.

This is of significance for budgeting and modeling the food needs of benthic-feeding apex predators such as gray whales, walruses, bearded seals, and diving sea ducks that may be impacted by the arctic biological changes that will be one of the foci of the

SEARCH research program. Future investigations will focus on the influence of environmental factors such as the cycling of chlorophyll within sediments over annual cycles. We will also investigate the validity of the 1.0 mm screen size in deeper waters where benthic macrofauna are quantitatively less important, such as on the outer continental shelf being studied in the Shelf-Basin Interaction program.

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Interannual Variability of the Distribution of the Types of the Halocline Within the Central Arctic Basin

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The shift in position of the frontal zone between the Atlantic- and Pacific-derived waters and the evolution of the cold halocline layer were the outstanding events which demonstrated the changes within the Central Arctic Basin during the 1990s. Similar events in the past were researched using the vast collection of observed temperature-salinity vertical profiles.

The profiles of the WOA-2001, MOODS, old Russian expeditions, and some recent measurements were examined for the search. The regions of the Arctic Basin between the Nansen Basin and the Alpha Ridge were under consideration. Every vertical profile that was deep enough to characterized temperature and salinity from the surface mixed layer up to Atlantic water was ascribed to one of the three types.

Profiles without cold halocline layer were attributed to the first type. Profiles with cold halocline layer were attributed to the second one. The second type of profile was also named as "Atlantic type of halocline." Profiles that included Pacific-derived waters were selected as third type, or "Pacific type of halocline". The primitive expert visual analysis of every profile was carried out to determine the type of profile. The "winter halocline" and "remnant halocline" layers were determined by expert analysis and were not under consideration.

It was established that the frontal zone between the Atlantic- and the Pacific-derived waters shifted from positions along the Lomonosov Ridge several times during the 20th century. At the same time, the disappearance of the cold halocline layer during the first half of the 1990s was the near unique event.

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Observing Ocean Fluxes Through Lancaster Sound of the Canadian Arctic Archipelago

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Since 1998 researchers from the Bedford Institute of Oceanography have been monitoring the volume, heat, and freshwater fluxes that pass through Lancaster Sound, one of the channels through the Canadian Arctic Archipelago. The aim of this ASOF-West project is to quantify the transports and realize their impact on the heat and freshwater budgets of the Arctic Ocean as well as their impact on the circulation and vertical ventilation of the North Atlantic and the global meridional overturning circulation (MOC).

Time series of salinity, temperature, and velocity, and the derived estimates of the volume, freshwater, and heat fluxes passing through Lancaster Sound show large seasonal and inter-annual variability. The 1998 to 2001 mooring data show that the annual mean fluxes are dominated by summer values. Heat fluxes are predominantly negative, which indicates that the arctic surface water cools the Atlantic. The freshwater ocean flux is generally 1/15 of the volume flux. Seasonal volume fluxes vary from fall/winter lows of 0.1 to 0.4 Sv to high summer values of 1.9 to 2.3 Sv, with the annual mean ranging from 0.5 to 1.2 Sv with a three-year mean of 1.0 Sv.

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Ice Seals as an Indicator of Change in the Arctic Marine Environment

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Ringed, bearded, spotted, and ribbon seals are the species of Alaska's seals collectively called "ice seals" because of their association with sea ice and their dependence on it for feeding, molting, and pupping. Ice seals are important components of the Bering-Chukchi Sea ecosystem, and because they represent different trophic niches they may be good indicators of changes in the marine prey assemblage. Population estimates for ice seals are not available and not easily attainable due to their wide distribution and the problems related to marine mammal surveys in remote, ice-covered waters.

With no other methods currently available to evaluate population status and trends for these species, population indices such as age at first reproduction, reproductive rate, body condition, and growth are especially important. By collecting tissue samples from seals harvested by subsistence hunters at selected locations we can begin to assess the health and status of each species. Contaminant levels and diet can also be addressed with a sampling program. Changes in prey available to seals can be determined by comparing diet data collected now with that collected in the 1960s, 1970s, and 1980s. Similarly, changes in reproductive rate, growth, and body condition would also be detectable by comparison. Our program has begun to collect samples at five locations. Once we have accumulated large enough sample sizes (by 2006) we will conduct comparisons across decades.

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Variability of Volume, Heat, and Freshwater Transports Through Fram Strait

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The main exchanges of volume, heat, and freshwater between the Arctic Ocean and the world ocean take place through Fram Strait, the only deep connection between the Arctic Ocean and the Nordic Seas. Warm Atlantic water enters on the eastern side in the West Spitsbergen Current, while cold, low-salinity polar surface water and sea ice, as well as denser Arctic Ocean intermediate and deep waters, exit to the west in the East Greenland Current. Since 1980 hydrographic sections extending across the entire strait have been occupied, and after the initiation of the VEINS programme in 1997 hydrographic sections have been taken every year. Geostrophically computed transports of volume, heat, and freshwater for ten years between 1980 and 2001 are presented. A water mass classification is adopted and in addition to the total in- out- and net transports, transports carried by the different waters are also given. The inflow volumes range mostly between 5 and 8 Sv (1,106 m^3s^{-1}) and the outflow volumes between 8 and 11 Sv with larger net outflow in recent years. The salinity of the inflow has decreased and a substantial amount of freshwater, possibly from the Barents Sea, has been added to the West Spitsbergen Current.

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Arctic Warming Through the Fram Strait in the Late 1990s

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We present estimates of volume and heat transport through the Fram Strait for the period 1997 to 2000 from data of moored instruments, and discuss them along simulations with a high-resolution ice-ocean model. The observed full-depth annual mean volume transports at 78° 55′N were in the order of 10 Sv both northward and southward with a net transport between 2 and 4 Sv to the south. The annual mean net heat transport across 78° 55′N increased from 16 to 41 TW. This resulted from a very strong increase in heat transport in the West Spitsbergen Current (from 28 to 46 TW) that was not compensated for by an equivalent signal in the southward flow. The heat transport to the south remained constant within error limitations. Only half of the heat flux increase in the West Spitsbergen Current was due to a higher temperature; half of it was due to a stronger flow. Model simulations explain the elevated temperatures in the WSC mainly by a reduced heat loss in the Norwegian Sea.

A similar increase as observed between 1997 and 2000 would have been sufficient to explain the warming of intermediate layers in the Eurasian Arctic observed in the early 1990s. Consequently, we suggest that the warming signal is presently spreading in the interior Arctic Ocean.

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Recent Sedimentation Processes and Transport Pathways of Terrigenous Material in the Kara Sea and the Adjacent Arctic Ocean

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In the frame of the joint Russian-German project, "Siberian River Run-Off (SIRRO): The Nature of continental run-off from the Siberian rivers and its behavior in the adjacent Arctic Basin," the influence and importance of river supply for biological, geochemical, and geological processes in the Kara Sea are investigated. In order to understand the recent sedimentation processes in this region surface sediments in Ob and Yenisei rivers and estuaries as well as in the Kara Sea are investigated for sedimentological (grain-size distribution, clay minerals, heavy minerals) and geochemical (major and minor element concentrations) proxies.

The rivers Ob and Yenisei drain large amounts of water and particulate matter into the Kara Sea and farther into the adjacent Arctic Ocean. From the composition of the surface sediments, the rivers Ob and Yenisei differ from each other. In the sediments of the Yenisei River, black ore minerals and smectite contents and the concentrations of Fe, Ni, Ca, Mg, and Ti are enhanced, compared with the sediments of the Ob River. Among other areas, the Yenisei River drains the Triassic flood-basalt consisting of the Putoran Mountains, which also show higher contents in these parameters. Material from the other areas dilutes the weathered matter from the basalts, so the mentioned elemental contents are not as high as in the basalts, but higher than in the average continental crust.

In the "marginal filter" of the Ob and Yenisei estuaries fine-grained material with an enhanced smectite content dominates. Especially, Mn-, Fe-, Ni-, and Co- concentrations increase in these "marginal filter" zones due to an increasing salinity by decreasing water velocity. In Ob estuary the "marginal filter" zone is extended from approximately 70° to 72°N, and in Yenisei estuary between ca. 71° and 73°N.

Indicated by enhanced Fe- and Ni- concentrations as well as higher smectite contents, recent pathways of terrigenous material in the Kara Sea are determined from the Yenisei Mouth northward to the St. Anna Trough and northeastward to the Vilkitzky Strait.

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New Data Products for the Study of the Climatic System of the Arctic Seas

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The World Data Center for Oceanography in Silver Spring, Maryland, is collaborating with the Murmansk Marine Biological Institute and the Zoological Institute in Russia to study climate changes in the Arctic and the impact on the development of marine life. This presentation will describe a database, which contains 430,000+ stations of physical and hydrochemical variables and 16,000+ plankton samples for the time period 1810–2001. A statistical analysis has been calculated for each month in order to develop criteria for quality control and to define the limits of variability within the data. Using this database, two time series have been created: 1) a seventy-year time series of temperature and salinity, at different depths, along the Kola section in the Barents Sea which quantitatively describes the variability of these two parameters; 2) a thirty-eight-year time series (from 1961–1998) of temperature, salinity, and zooplankton at a fixed point in the White Sea. This time series consists of three components: a) yearly variability of temperature and salinity anomalies at different depths for the period of time; b) climatological annual cycle of development for sixty-five zooplankton species; and c) the annual cycle of development for these species as a function of temperature and salinity. This time series allows one to describe in quantitative terms the impact of climate variability on the development of zooplankton.

Multi-Disciplinary Investigations at an Arctic Deep-Sea Long-Term Station

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The deep sea represents the largest ecosystem on earth. Due to its enormous dimensions and inaccessibility, the deep-sea realm is the world's least known habitat. To understand ecological ties, the assessment of temporal variabilities is essential. Only long-term investigations at selected sites, describing seasonal and inter-annual variations, can help to identify changes in environmental settings determining the structure, the complexity, and the development of deep-sea communities. The opportunity to measure processes on sufficient time scales will also help to differentiate between natural variabilities and environmental changes due to anthropogenic impacts.

High latitudes are among the most sensitive environments in respect to climate change, a fact urgently demanding the assessment of time series, especially in polar regions. AWI- "Hausgarten" represents the first and only deep-sea long-term station at high latitudes. Following a pre-site study using the French ROV "VICTOR 6000," "Hausgarten" was established in summer 1999 in the eastern Fram Strait west of Spitsbergen. Beside a central experimental area at 2,500 m water depth, we defined nine stations along a depth transect between 1,000–5,500 m, which are revisited yearly to analyze seasonal and inter-annual variations in biological, geochemical, and sedimentological parameters. In summer 2003, the number of permanent stations was increased to a total of fifteen stations by introducing additional sampling sites along a latitudinal transect following the 2,500 m water depth isobath.

To characterize and quantify organic matter fluxes to the seafloor, we use moorings carrying sedimentation traps. The exchange of solutes between the sediments and the overlaying waters as well as the bottom currents are studied to investigate major processes at the sediment-water interface. A free-falling device carrying respiration chambers, and a micro-profiler being positioned and activated by a ROV are used to assess the oxygen consumption by the benthic community. Gradients in oxygen are also measured from bottom water samples in order to quantify interfacial solute fluxes (including nutrients) and metabolic rates in the benthic boundary layer. These investigations are completed with the use of current meters, handled by the ROV.

A multiple corer is used to retrieve virtually undisturbed sediment samples. Vertical gradients of nutrients, Corg contents, C/N ratios, porosity, and other geochemical parameters are determined to characterize the geochemical milieu of the upper sediment layers. Near-surface sediments are also sampled with the giant box corer for sedimentological, mineralogical, and micropaleontological investigations, to assess source areas for the sediments.

Biogenic sediment compounds are analyzed to estimate activities (e.g., bacterial exo-enzymatic activity) and total biomass of the smallest sediment-inhabiting organisms. Results will help to describe the eco-status of the benthic system. The quantification of benthic organisms from bacteria to megafauna is a major goal in biological investigations.

A number of in situ experiments installed in 1999 and 2001 will help to identify factors controlling the high biodiversity in the deep sea.

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The Circulation of Summer Pacific Water in the Arctic Ocean

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We present an analysis of Arctic Ocean hydrographic and sea ice observations from the 1990s, with a focus on the circulation of water that originates in the North Pacific Ocean. Hydrographic data from icebreaker and submarine cruises, as well as aircraft-based operations, are discussed. We trace Pacific water throughout the western Arctic Ocean, including the area north of Ellesmere Island, Canada, where observations have recently been taken as part of the North Pole Environmental Observatory (NPEO). NPEO consists of air, sea, and ice studies performed each spring since 2000 in the vicinity of the North Pole, with a base of operations at Alert, Ellesmere Island.

Previous studies have shown the presence of two varieties of relatively warm “summer water” in the vicinity of the Chukchi Sea, i.e., the relatively fresh Alaskan Coastal Water (ACW) and the relatively saltier summer Bering Sea Water (sBSW). Here we extend these studies by tracing the circulation of these waters downstream into the Arctic Ocean. We find that ACW is generally most evident in the southern Beaufort Gyre, while sBSW is strongest in the northern portion of the Beaufort Gyre and along the Transpolar Drift Stream. We find that this separation is most extreme during the early-mid 1990s, when the Arctic Oscillation was at historically high index values. This leads us to speculate that the outflow to the North Atlantic Ocean (through the Canadian Archipelago and Fram Strait) may be similarly separated. Some of this outflow may be influenced by an eastward-flowing current along the continental slope that our limited data indicate may be mostly composed of ACW, at least downstream of Alaska. As Arctic Oscillation index values fell during the later 1990s, ACW and sBSW began to overlap in their regions of influence. These changes are evident in the area north of Ellesmere Island, where the influence of sBSW is highly correlated, with a three-year lag, with the Arctic Oscillation index. We also note that winter Bering Sea Water (wBSW) seems to generally follow the circulation of sBSW in the Arctic Ocean. Altogether, this brings the number of distinct Pacific water types in our Arctic Ocean inventory to three: ACW, sBSW, and wBSW.

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Short-term Variability of River Discharge in the Kara Sea (Arctic Ocean) and Environmental Significance

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The present state of the Arctic Ocean strongly depends on large river discharge. A significant increase in Siberian river discharge, associated with a warmer climate and enhanced precipitation in the river basins, has been observed during the past decades. The variability in river discharge seems to be related to a cyclic variation of the Northern Hemisphere/arctic atmospheric circulation pattern, i.e., the “Arctic Oscillation (AO)” and the “North Atlantic Oscillation (NAO).” With the importance of river discharge in mind, a Russian-German research project on “Siberian River Run-off (SIRRO)” was initiated to study in detail the freshwater discharge and its short-term variability in space and time (Stein et al., 2003 and further references therein).

Based on the investigation of surface sediments, magnetic susceptibility (MS) data can be used as proxy for Yenisei river discharge into the Kara Sea. The MS records of selected sediment cores from high-sedimentation rate areas of the Yenisei estuary indicate a distinct short-term (decadal, centennial to millennial) variability through Holocene times. This variability may reflect natural cyclic climate and river-discharge variations, which might be seen in context with the inter-annual and inter-decadal environmental changes recorded in the high northern latitudes over the past decades, such as, for example, the NAO/AO pattern. Positive NAO/AO phases bringing warm and wet air to the Russian Arctic and causing increased surface temperatures, precipitation, and weathering, may have been the trigger for increased riverine input from the Putoran Massif throughout the Holocene. This hypothesis, which is important within the ongoing debate about naturally versus anthropogenically driven future climate change, however, has to be proven by further high-resolution multi-proxy arctic climate records.

Reference:

Stein, R., K. Fahl, D.K. Fütterer, E.M. Galimov, and O.V. Stepanets (Eds.), 2003. Siberian River Run-off in the Kara Sea: Characterisation, Quantification, Variability, and Environmental Significance, *Proceedings in Marine Sciences* Vol. 6, Elsevier, Amsterdam, 484 pp

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Effects of Variability in Hydrographic Structures on Biological Activity in Bering Strait Over Four Years, 2000–2003

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The long-term monitoring of the inflow into the Arctic Ocean through the U.S. side of Bering Strait has been conducted over the last four years. The inter-annual variation of nitrate concentration and phytoplankton biomass in the strait were large as a result of different physical structures among the different seasons and years. For example, the physical structure observed in 2002 was unusual due to southward wind and current flows. As a result, low-salinity Alaska Coastal Water (ACW with salinity < 31.8 psu) spread westward on top of higher-nutrient and more saline Bering Shelf Water (BSW with $31.8 < 32.5$ psu) extended eastward on the bottom. Eventually, more nitrate was available on the eastern side of Bering Strait and thus more phytoplankton activity was observed in 2002 than in any of the other years. In contrast to that, nitrate concentrations in 2000 were almost depleted when ACW occupied most of the strait and, as a result, the phytoplankton biomass was lowest for the four observation periods. From the limited spatial sampling it appears that the overall fertilization of BSW maintained enhanced biological conditions on the western side of Bering Strait, except in 2000, at least through early September each year.

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Arctic Oscillation and Inter-annual Variations of Heat Flux Associated with Oceanic Upwelling

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The Arctic Oscillation (AO) is a leading mode of inter-annual and decadal variability in the Arctic. The surface wind stress associated with the AO forces surface oceanic circulation, shifting between a cyclonic and an anti-cyclonic state.

The convergence of the surface Ekman transport, and thus the upwelling rate, vary profoundly between these two states. The change of the oceanic heat flux associated with the upwelling in the difference phases of an AO cycle will be presented and compared with the magnitude of surface heat fluxes.

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Hydrographic Changes in Baffin Bay, 1916-1999

Melissa Zweng University of Delaware

Student Poster

Baffin Bay serves as a conduit for arctic water to enter the Labrador Sea, as well as for Atlantic water to enter the Arctic Ocean. The temperature and salinity in different regions of Baffin Bay have changed significantly in the period between 1916 and 1999. Most notably, the warm West Greenland Current has increased in temperature at a rate of up to 0.2º C per decade, and this warming appears to have affected the deepest waters of Baffin Bay as well. The water of the Baffin Island Current has also shown a freshening trend.

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Polar Optimized WRF for Arctic System Reanalysis of Arctic Meteorology over Recent Decades

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To gain a better understanding of arctic climate change over recent decades, a high-resolution comprehensive Arctic System Reanalysis (ASR) of the atmosphere, ocean, and land surface is planned. To best understand the processes and feedbacks impacting climate change, we require high-quality representations over a long time series of temporally and dynamically consistent fields. Reanalyses combine a short-term model forecast with all available observations (from the ground, rawinsondes, aircraft, satellites, etc.) to provide optimum analyses of directly measured fields. Short-term forecasts also produce fields that are incompletely monitored or unmeasured (precipitation, evaporation, clouds, etc.) The planned ASR allows a synthesis of several arctic field programs (SHEBA, LAII/ATLAS, ARM) in a physically consistent framework. The high-resolution ASR benefits from the lessons learned during the earlier global reanalyses [National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), and ECMWF]. The ASR will eventually encompass a highly detailed treatment of the coupled atmosphere-land-ocean system. The work toward this goal will begin with the atmosphere, with the land and ocean components to follow.

To begin the groundwork for the ASR, the Weather Research and Forecasting (WRF) model is being specially adapted for the polar regions. The WRF is currently in the later stages of development by NCAR and NCEP, and early versions of the model are already available. The WRF is the successor to the Penn State/NCAR Fifth Generation Mesoscale Model (MM5). The polar-optimized version of the new model is the natural choice as the algorithm for the upcoming Arctic Reanalysis. NCAR is developing a robust three-dimensional variational assimilation for WRF to best incorporate the modern arctic in situ and remote sensing data. Moreover, a high-latitude physics package has been previously developed for MM5 by the Polar Meteorology Group of the Byrd Polar Research Center. Based upon this earlier work, improvements to the simulation of cold cloud and the implementation of mixed sea ice and open water grid points are among the adaptations being applied in Polar WRF. The current model, Polar MM5, is used for a variety of applications including real-time Antarctic numerical weather prediction, climatic studies of the El Niño-Southern Oscillation (ENSO) linkage to Antarctica, and studies of the hydrology of arctic river basins. Verification of Polar MM5 versus observations indicates that the model performs well for the high-latitude regions of both hemispheres.

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Pan-Arctic Contaminant Landscapes: Status and Change

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Assessing spatial patterns of contaminant distribution across the Arctic is a challenging task, but one that is of considerable importance to local subsistence harvests, the understanding of pan-arctic contaminant biogeochemistry, and international policy on contaminant controls. The primary substances of concern are semi-volatile elements and compounds that tend to bioaccumulate and have the potential to compromise immune function, reproduction, and neurobiology (including intellectual function) in higher vertebrates. These include, primarily, mercury (Hg) and persistent organic pollutants (POPs), an operationally defined group of halogenated (Cl, Br, F) compounds. Lead (Pb) and cadmium (Cd) have also been of some interest. The recent (2003) Arctic Monitoring and Assessment Programme (AMAP) reports on heavy metals and POPs, providing state-of-the-science perspectives on the pools, pathways, temporal trends, biological effects, and known information gaps. Briefly, identification of spatial patterns is hampered by insufficient well-documented, intercalibrated spatial information on appropriate matrices. For example, there may be a bull's eye of Hg accumulation among high-order marine predators in the eastern Canadian high Arctic and western Greenland. If true, this would be of substantial importance for subsistence users throughout the Arctic, among both affected and much less affected communities. However, the evidence underlying this pattern is not completely robust. Faunal studies are confounded by trophic interactions and migratory behavior that can and will change with changing climate. Evidence from lake sediment cores, which are thought to track atmospheric deposition, is still controversial. Further, key elements of arctic biogeochemical cycles are still being revealed (e.g., Hg depletion events, differences in transport among a-, b-, and g-hexachlorocyclohexane, oceanic pathways for contaminant Pb), and the relationship of these to contaminant accumulation in inland vs. coastal vs. marine systems is as yet obscure. This paper will briefly summarize key issues and information gaps, and identify opportunities for cross-linkages with research on atmospheric, fluvial, and oceanic fate and transport, as well as subsistence issues and related effects on human communities.

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New Satellite Observations of Recent Change in the Arctic Climate

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Measurements of a wide variety of arctic parameters suggest that the region has experienced a rapid, large-scale, and perhaps unprecedented change in the past two decades. Over much of the Arctic Ocean, however, surface and atmospheric data are sparse. This void contributes to our incomplete understanding of fundamental arctic variability, deficiencies in model representations of climate processes, and recently highlighted inaccuracies in reanalysis products. Retrievals from polar-orbiting satellites offer a partial solution for this predicament. In this presentation, observed basin-wide changes in several new products derived from twenty years of retrievals from the TIROS Operational Vertical Sounder (TOVS) will be discussed. These products will likely include upper-level wind fields, advection of heat and moisture, net precipitation, surface longwave radiation, cloud parameters, and surface temperatures.

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Variability and Trends in the Arctic Climate as Simulated with the Bergen Climate Model

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The Bergen Climate Model (BCM) has been applied to perform a five-member ensemble of 1% per year CO_2-increase experiments. Initial conditions have been taken from a 300-year control integration with the BCM. Each experiment has been initialized at different strengths of the Atlantic Meridional Overturning Circulation (AMOC), and integrated for eighty years until doubled CO_2 is reached.

We will here present results from the control and perturbation simulations, with focus on the climate variability and trends of the Arctic. In the control integration, BCM realistically simulates the North Atlantic/Arctic Oscillation (NAO), and its observed impacts on sea surface temperature and sea ice distribution. In four out of five perturbation runs, NAO has a trend toward a more positive phase, while in the fifth experiment, extremely negative values during the last decades make the trend flat. Typically the NAO increase is in the order of one standard deviation during doubling of CO_2. At doubled CO_2, the annual ensemble mean shows 15% more precipitation in Arctic, and a warming of 3.5º C. Both the changes and the spread in response among the different members are largest in wintertime. In all perturbation runs, the sea ice area shows a steady decrease. After doubled CO_2, the winter ice maximum has retreated from the Barents Sea, and the entire Arctic is ice-free during summer. The strength of the AMOC has a negative trend in all members of the ensemble, with a typical decrease of 10% over the eighty years. A similar reduction is not found in the inflow of Atlantic Water to the Nordic Seas. The arctic climate response to the CO_2 increase is strong compared with what is found in other models. This is due to the additive effects of a small reduction in the AMOC and maintenance of the oceanic energy transport into the Arctic, increased NAO that increases the atmospheric energy transport into the Arctic, and the general warming due to increased CO_2.

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Pan-Arctic Change over the Instrumental Record

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We review recent changes in the Arctic over the last four decades through examination of eighty-six regionally dispersed time series representing seven physical and biological data types. These changes are put into a century-long context of surface air temperature (SAT) records beginning in 1886. The temporal pattern of recent change, as calculated from Principal Component Analysis, has a single regime-like shift near 1989 based on a large number of indices including stratospheric temperatures, the Arctic Oscillation (AO), sea ice declines in several regions, and selected mammal, bird, and fish populations. Almost all terrestrial variables and sub-arctic sea ice extents have a more linear trend. Central arctic variables show an inter-decadal variability, which can be traced back to the 1950s (Vinje 2001).

While there is a particularly strong wintertime decadal signal in the North Atlantic region historical SATs, long-term changes in the remainder of the Arctic are most evident in spring, with generally cool temperatures before 1920 and arctic-wide warming in the 1990s. There are regional/decadal warming events in winter and spring in the 1930s to 1950s, but meteorological analysis suggests that these are the result of intrinsic variability in regional flow patterns. These mid-century events contrast with an arctic-wide AO influence in the 1990s.

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Variability of Arctic Cloudiness from Satellite and Surface Data Sets

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Our knowledge about the variability of arctic cloudiness has been very limited. We basically know its annual cycle and have a rough climatological sense that some areas are cloudier than others.

This is changing. Satellite-derived data sets from the NASA Polar Pathfinder projects allow us to go beyond this and investigate the temporal and spatial variability of clouds in the polar regions.

In this paper we will present results from the TOVS Polar Pathfinder project. We will present changes over the period 1980-98 and compare those with data from other satellite data sets and surface observations. TOVS and AVHRR-based observations both show a significant 5% increase in cloud fraction over the Arctic Ocean during spring and a similar decrease in cloud fraction during winter. Regional changes are even larger. We will investigate the effect of these changes on the surface radiation balance and study the implications of cloud variability on sea ice through modeling experiments.

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Governing Large-Scale Control in Arctic Modelling

Hans von Storch GKSS Research Center

Regional atmospheric modelling is a downscaling problem. Large-scale atmospheric states are determined by the sphericity of Earth, the meridional radiative contrast, the land-sea-sea ice distribution, the orography determine and the large-scale chaotic dynamics. The regional statistics are due to regional and local chaotic dynamics, conditioned by the large-scale state. In areas with efficient "flushing," as in Western Europe, the time scale for forming a broad range of equivalent but different regional states is generally too short. However, in the Arctic, which cannot be considered a through-flow region, considerable variability is emerging when several regional atmosphere simulations are run with identical boundary values but slightly different initial conditions. Thus, not surprisingly, the arctic circulation is not efficiently governed by lateral boundary values.

The spectral nudging, or large-scale control concept is a suitable approach to force the model to adopt prescribed (e.g., analyzed) large-scale states, while developing realistic, detailed, regional features consistent with the large scale and the physiographic detail.

The method is described, and examples for the performance shown.

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Modeling Atmospheric Transport of Trace Pollutants to the Arctic: Source-to-Receptor Air Transfer Coefficient Maps: A Tool to Show How Changes in Weather, Climate and Emissions Can Change Contaminant Source Pathways and Deposition Patterns

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Air Transfer Coefficient (ATC) maps are in a very limited sense similar to back trajectories, but include much more information than a center line of air movement. The ATC maps represent the environmental fate of a particular contaminant between the source and the receptor: vertical and horizontal dispersion, atmospheric degradation, deposition en route, and the final result, the fraction of the pollutant originally emitted that deposits at the receptor, the air transfer coefficient. The ATC can be multiplied by a known or hypothetical source emission to yield the amount deposited to the receptor.

ATC maps are a product of a CBNS adaptation of NOAA's numerical atmospheric dispersion model HYSPLIT to simulate environmental fate of trace contaminants with meteorological data. CBNS ATC maps presented in this poster include monthly and annual average ATC maps showing how changing weather patterns affect the long distant atmospheric transport of dioxin from North America to selected arctic Nunavut communities and hunting grounds.

We propose to extend this work to other Northern Hemisphere source regions (Japan, Asia, and Europe); add geographical and ecological receptors in Alaska (hunting grounds, biodiversity, polynyas); model years with historical meteorological data to investigate climate change (e.g., arctic oscillation); apply new emission source inventories and future emission scenarios (e.g., growth in China, emission reduction in Canada and the U.S.); distinguish local sources from distant sources (e.g., use the new Alaskan dioxin emission inventory by NACEC); adapt the model for surface-air exchange (oceans, lakes, land surface, vegetation); and model additional trace contaminants measured in the arctic (e.g., PCB, PAH, pesticides).

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Core Atmospheric Measurements at the Summit, Greenland, Environmental Observatory: GEOSummit

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A program was recently implemented for long-term measurements of the arctic atmosphere, snow, and other Earth-system components at the Summit, Greenland, Environmental Observatory (GEOSummit), located at an elevation of 3,100 m on the Greenland ice sheet. GEOSummit was the site of the Greenland Ice Sheet Project 2 (GISP2) ice core drilling, completed in 1993, and has been a site of atmospheric, snow, and other geophysical measurements since then. It is currently the only high-altitude site for continuous atmospheric and related measurements in the Arctic. Many of these measurements, previously made intermittently at GEOSummit, resumed on a continuous basis beginning in summer 2003 and will be publicly available.

There are three main science drivers for the measurement program. First, core atmospheric and snow measurements provide a baseline for the continued operation of GEOSummit as a long-term site for year-round measurements of climate change indices. Second, a number of processes that could amplify atmospheric change need consistent measurements and systematic study. For example, recent evidence indicates that important atmospheric chemical constituents undergo temperature-dependent exchange with ice/snow, and that some species are photochemically transformed and/or produced within the sunlit surface snowpack. The availability of the GEOSummit measurements encourages and facilitates multi-disciplinary research by providing a high-quality core of baseline observations. Third, current investigations to determine the long-term cycling, seasonality, and preservation of key compounds in the surface snow, and their relation to paleoclimatic records preserved in ice cores, use the year-round records made available through GEOSummit. Because changes in arctic atmospheric circulation are cyclic over periods of 4–5 years and greater, long-duration measurements are critical to place observed changes in a long-term perspective.

The current program continues and expands the core baseline measurements at GEOSummit for a five-year period, beginning in summer 2003. GEOSummit is currently a partnership between NSF-OPP, NOAA-CMDL, and investigators from Denmark, Germany, and Switzerland. Baseline measurements include meteorology, radiation, tropospheric and aerosol chemistry, snow properties, and snow chemistry as well as carbon cycle compounds, chlorofluorocarbons, radiation, and ozone. Average water accumulation at GEOSummit is 21 $g/cm^2 y^{-1}$, with annual patterns varying significantly from year to year. The mean annual temperature is ~-30^o C, varying between -70^o and 0^o C. Near-surface summertime ozone averages 55 ppbv. Aerosol fluxes and atmospheric gas concentrations (e.g., O_3, CO, CO_2, CH_4) exhibit characteristic annual cycling.

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The National Oceanic and Atmospheric Administration (NOAA) SEARCH Initiative

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NOAA is one of eight federal agencies participating in the implementation of the SEARCH science plan. With a mission to understand and predict changes in the Earth's environment, and conserve and manage coastal and marine resources to meet the Nation's economic, social, and environmental needs, NOAA has a particularly important role to play in SEARCH. Two of NOAA's strongest attributes are established observation and modeling capabilities. The observational component includes acquisition and archiving of both regional and global-scale environmental data sets. The modeling component includes ingestion of these data into forecast and climate models for forecasting, hindcasting, and nowcasting.

NOAA has initiated its SEARCH program with seed activities that address high-priority issues relating to the atmosphere and the cryosphere. The three primary foci of the current program include:

- Establishing long-term radiation, cloud, and aerosol Arctic Atmospheric Observatories to improve detection of environmental Arctic change in the lower and upper atmosphere.
- Initiation of a long-term international program to document and attribute changes in ice thickness through direct measurements and modeling.
- Reanalysis of NOAA satellite data (TOVS radiances), surface observations (data rescue, acquisition, development of interdisciplinary climate indices) and model outputs (NCEP and Arctic WRF) and development of a near real-time Arctic Change Detection System.

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FIRE.ACE Cloud Microphysical Observations and Their Parameterization: Emphases on Cloud Cover and Integration of Observations

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The purpose of this presentation is to summarize the arctic cloud microphysical observations collected during the First International (ISCCP) Regional Experiment-Arctic Cloud Experiment (FIRE.ACE) flights made over the Surface Heat Budget of the Arctic (SHEBA) and Beaufort Sea area in April 1998. The observations were collected with instruments mounted on the National Research Council (NRC) Convair-580 of Canada. The main observations were temperature, dew-point, ice and liquid particle size, concentration, aerosol size and concentration, condensed water content, and 3-D wind measurements. The observations were analyzed along constant-altitude flight legs and used to generate profiles.

The results showed that in situ observations can be used for validating model results, verifying remote sensing observations, and studying turbulent fluxes over leads and polynyas, airmass effects on cloud formation, and cloud cover parameterizations. Integration of observations indicated that in situ observations were a vital part of comparisons. The conclusion is that ice nucleation processes need accurate measurements of ice particles at small sizes to better understand the arctic cloud physical processes, e.g., ice nucleation and particle growth, that were extensively used in radiative and moisture budget calculations. These results are directly related to the goals of the Studies of Environmental Arctic Change (SEARCH) program.

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The Urban Heat Island in Winter at Barrow, Alaska

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The village of Barrow, Alaska, is the northernmost settlement in the United States and the largest native community in the Arctic. The population has grown from about 300 residents in 1900 to more than 4,600 in 2000. In recent decades, a general increase of mean annual and mean winter air temperature has been recorded near the center of the village, and a concurrent trend of progressively earlier snowmelt in the village has been documented. Satellite observations and data from a nearby climate observatory indicate a corresponding but much weaker snowmelt trend in the surrounding regions of relatively undisturbed tundra. Because the region is underlain by ice-rich permafrost, there is concern that early snowmelt will increase the thickness of the thawed layer in summer and threaten the structural stability of roads, buildings, and pipelines.

Here we demonstrate the existence of a strong urban heat island (UHI) during winter. Fifty-four data loggers were installed in the ~150 km^2 study area to monitor hourly air and soil temperature, and daily spatial averages were calculated using the 6–7 warmest and coldest sites. During winter (December 2001–March 2002), the urban area averaged 2.2° C warmer than the hinterland. The strength of the UHI increased as wind velocity decreased, reaching an average value of 3.2° C under calm (< 2 m s^{-1}) conditions and maximum single-day magnitude of 6° C. UHI magnitude generally increased with decreasing air temperature in winter, reflecting the input of anthropogenic heat to maintain interior building temperatures. On a daily basis, the UHI reached its peak intensity in the late evening and early morning. There was a strong positive relation between monthly UHI magnitude and natural gas production/use. Integrated over the period September–May, there was a 9% reduction in accumulated freezing degree days in the urban area. The evidence suggests that urbanization has contributed to early snowmelt in the village.

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Arctic Modes of Temperature Variability During the Past 500 Years: Relating Summer to Winter

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A circum-arctic array of paleoclimate records provides for the identification and reconstruction of warm-season (May through October) arctic modes of variability over the past 500 years. The paleoclimate array is composed of tree rings, varved lake sediments, and ice layers, most of which are annually resolved. The array's leading Empirical Orthogonal Functions (EOFs) are significantly correlated with the leading EOFs of warm-season temperature variability from the NCEP-NCAR reanalysis. These EOFs can be identified with 1) changes in mean temperature, 2) the Arctic Oscillation, and 3) a Urals Trough wave number three circulation pattern.

A major question is the relationship of these warm-season modes of variability with their cold-season counterparts. This relationship is explored in the context of 1) pressure and temperature variability in the NCEP-NCAR reanalysis over the past fifty years, and 2) temperature variability in the Climate Research Unit's gridded compilation over the past 140 years. Insights are used to interpret the warm-season paleoclimate reconstructions in the context of the full-annual variability of arctic temperatures. This aids in putting recent positive trends in the Arctic Oscillation and mean arctic temperature in perspective with the natural background variability of the arctic system.

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Structure of Surface Level Pressure (SLP) Variability Over the Arctic from 1948–2001 and Future Climate Change

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The weather of the northern countries depends on the state of the atmosphere over the Arctic. We investigate the structure of variability of SLP over the Arctic, including the synoptic nature of its components and the temporal tendency associated with recent climate change. The daily SLP fields above the Arctic for 1948–2001 (NCEP/NCAR) are analyzed using Empirical Orthogonal Functions (EOFs). The basis of the investigations was a temporal variability of the factors of the decomposition of the daily SLP fields by annual EOF for 1948–2001.

The results of the study are:

1. The first six EOFs account for 88% and 80% of the total SLP variance in the Arctic during February and August, respectively. EOF 1 accounts for about 32% of this variance. EOF 2 accounts for 21%. EOF 3 accounts for 13%.
2. The melting of snow during spring along coasts in the latitude zone 50°–60°N is closely correlated with the monthly variability of EOF 1. This correlation between EOF 1 and snowmelt is larger than the correlation between EOF 1 and incident solar radiation.
3. The monthly variability of EOF 2 is closely correlated with the month anomalies of incoming solar radiation in the latitude band 57.5°–82.5°N.
4. The monthly variability of EOF 3 is closely correlated with the variability of the SLP anomaly over the Beaufort Sea, i.e., where the Arctic Anticyclone (AA) occurs in the climatology.
5. To study the synoptic core of each physical factor, we approximate the mean monthly SLP field as a linear combination of EOFs 1–6.
6. The time series of the annual indices for EOFs 1–6 over 1948–2001 does not exhibit a pronounced, monotonic trend, such as one might expect in a hypothetical warming of climate.

7. The recent tendency of temporal variability of EOFs 1–6 may be interpreted as a relaxation of the AA and a deepening of the Climatic Cyclone over the Norwegian Sea. If continued, this tendency would have important consequences for the weather northern countries.
8. The penetration of blocking anticyclones from Europe and Eastern Siberia to the North Pole has a pronounced periodical character (3–4 years). At present, the intensity of the penetration and associated meridional air mass transfer is decreasing; hence, the intensity of zonal of air mass transfer is increasing.
9. Using the spatial scale of SLP variability over Arctic, we developed a quantitative classification of the daily SLP fields. From this we computed basic statistics and developed a New Modification (NM) of the Objective Analysis Method (OAM). The given method was successfully tested on cases of SLP pattern effects on the drift of position buoys in the Arctic Ocean. The NM is about 50% better than the existing OAM.

Thus, these results could be useful for understanding the nature of arctic SLP variability and for defining the future temporal tendency of the climate change.

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Long-Term Variability of Free Atmosphere in the Arctic

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We provide a short description of a database created by IARC and AARI using unified modern techniques. The first version of the data set contains radio soundings executed north of 65°N on the Russian coastal and island polar stations (more than one million soundings). Together with existing archives, this new data set, after additional control and improvement, will make it possible to investigate seasonal and inter-annual variability of the main parameters of the troposphere, stratosphere, and atmospheric boundary layer. The data will also be used to obtain new estimates of energy and moisture fluxes across the 70th parallel. Additionally, the final version of the improved and extended data set from the "North Pole" drifting stations (up to 33,000 soundings) have been prepared and are now available for analysis.

Preliminary investigations of the free atmosphere above the Canadian Arctic Basin, based on the "North Pole" data, showed that in 70% of the winter soundings the inversion base was at the surface; boundary layer height did not exceed 200 m; and mean temperature gradient in the inversion layer was 0.5–1.0 C0/100 m. Low-level jets were found in 30% of the soundings. During the investigated period (1955–1991) the boundary layer height and surface inversion depth tended to decrease; the vertical temperature difference through the inversion tended to increase in rough agreement with the index of atmospheric vorticity.

Long-term variations of the free atmosphere temperature and humidity in the North Polar Region (60–90 N) have been investigated using the original database, which combines the results of soundings on 116 aerological stations, ship observations and observations on the drifting stations "North Pole". The analysis of temperature trends for 1959–2000 shows that the mean air temperature in the North Polar

Region increased in the low and middle troposphere (850–400 hPa) and decreased in the upper troposphere and in the stratosphere. At the same time, the total energy of the polar atmosphere attributed to the so-called "mean energetic level" does not show any identifiable trends but does show long-term variation. Preliminary estimations of temporal variability of mean specific humidity on 850, 700, 500, 400, and 300 hPa levels showed a pronounced increase from surface to 850 hPa, and decrease above 850 hPa.

Quite preliminary examination of the data from the polar station on the Dickson Island with the longest period of record showed that the warming in the Arctic during the 1930s was quite different from recent. During that time the temperature increased in the whole troposphere and low stratosphere, in comparison with the recent increase of air temperature in the low troposphere and its decrease in the upper troposphere and stratosphere.

Our future plans include creation of a complete historical data set of the soundings; comprehensive statistical analysis of spatial-temporal variability of the main characteristics of the free atmosphere; estimation of energy and water vapor exchange with middle latitudes under different types of atmospheric circulation; and comparison with NCEP-NCAR and ECMWF reanalysis.

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A Novel Analytical Approach Greatly Expands Ice Core Records of Climate Change and Industrial Pollution

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Detailed records of biogeochemistry, atmospheric transport processes and pathways, volcanism, biomass burning, industrial pollution, and dust deposition are archived in glaciers and ice sheets. Although high-resolution analytical methods were developed over the past decade for a few soluble chemical species and ions, traditional ice core chemical measurements were based on discrete sampling, thereby limiting depth resolution and the range of depths sampled. We recently developed a method for making continuous, very-high-resolution measurements of a broad spectrum of trace elements in ice cores. A continuous ice core melter is connected directly with a traditional continuous flow analysis system to a double focusing inductively couple plasma (ICP) mass spectrometer and ICP emission spectrometer. Longitudinal samples of an ice core are melted in sequence, with the meltwater from the uncontaminated inner region of the sample fed to the analytical instruments in real time.

We applied this new method to ice cores from Greenland to develop a continuous record of total (soluble and insoluble) Na, Mg, Al, S, Ca, Y, Cr, Mn, Fe, Co, Cu. Rb, Sr, and Pb concentrations. These high-resolution measurements, which correspond to recent decades to centuries and have temporal resolutions of ~25 samples yr^{-1}, provide important new insights about the sources of impurities found in Greenland and about atmospheric transport processes. For example, while previous studies of Pb deposition during recent decades assumed that leaded gasoline emissions were the dominant source of Pb in central

Greenland, our continuous measurements show that ~50% of the increases in annual Pb flux and crustal enrichment from preindustrial levels to the 1970 maximum occurred from 1870 to 1890, more than fifty years before the introduction of leaded gasoline, thus suggesting that North American smelters and coal burning were likely sources.

The high temporal resolution and broad spectrum of analytes afforded by this new method provide unprecedented details of long-term changes in atmospheric chemistry and transport, leading to a better understanding of the impact of climate and human activities on the biogeochemistry of Greenland and the remote Arctic.

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Model Estimates of Wind Stress in Nares Strait and Smith Sound

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As part of an observational program to estimate freshwater fluxes through the Canadian Archipelago, a multiply nested mesoscale model is used to estimate wind stress in the Nares Strait and Smith Sound channels west of Greenland. The high-resolution model fields will be compared, where possible, with other available model products and observations. Preliminary results are presented and discussed.

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Simulated Changes in the North Atlantic Climate in an Ensemble of CO_2 Increase Experiments with the Bergen Climate Model

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A coupled global climate model (Bergen Climate Model) has been applied to perform a five-member ensemble of 1% per year CO_2 increase experiments. Initial conditions have been taken from a 300-year control integration with the BCM. Each experiment has been initialized at different strengths of the Atlantic Meridional Overturning Circulation (AMOC), and integrated for eighty years until doubling of CO_2 was reached.

The response of the Arctic to increased CO_2 showed a large spread, with the difference related to the initial state and the fate of the AMOC. The differences were especially pronounced for wintertime where the simulations starting with low AMOC gave higher arctic temperature and precipitation changes (approx. 30–40% increase in change during wintertime). The increased warming in the low initial AMOC state simulations seems related to the additive effect of a small reduction in the AMOC, which maintains the oceanic energy transport into the Arctic and the warming due to increased CO_2.

The results emphasize the role of the initial state and fate of the AMOC in modelled arctic response to increased greenhouse gases, and might provide helpful in determining the uncertainties in climate change simulations related to oceanic energy transport and the feedback of the changes in oceanic energy transport on the atmospheric energy transport.

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Preliminary Studies of Regional Variability in Arctic Cloud Properties

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At present, the only continuous measurements of arctic surface radiation, clouds, aerosols, and chemistry sufficient for detailed evaluation of interactive climate change processes in the lower atmosphere (0–15 km) are made in Barrow, Alaska. The Barrow facilities include the National Weather Service (with records from the 1920s), the NOAA/CMDL Baseline Observatory (in operation since 1972), and the DOE ARM North Slope of Alaska (NSA) site (in operation since 1998). It is the intention of the Atmospheric Observatory Element of the NOAA/SEARCH program to mirror the intensive Barrow atmospheric measurements, first in northeastern Canada and at some later date in central Siberia.

The Canadian and Siberian regions have been selected based on the principal hypothesis of the SEARCH program that arctic climate change is related to the Arctic Oscillation (AO). There have been observations of large-scale spatial co-variability among a number of climatic variables (surface temperatures, hydrological balances, cloud cover, winds) with the primary modes of the Arctic Oscillation. Analyses suggest that one of the most significant AO-related trends over the past fifty years is warming in Eastern Siberia and cooling in the northeastern Canada–western Greenland region. The Barrow site appears to be in a region of lower variability with respect to the AO, thus additional measurements in the regions where AO-related variability is expected to be the most pronounced are desirable. It is expected that instruments will be deployed in either Resolute or Eureka, Canada beginning in 2004.

In this presentation, a brief summary is made of the planning and goals for this new Atmospheric Observatory. In addition, surface observations, model results, and satellite data are used to make a preliminary analysis of the long-term regional variability of cloud properties in Barrow, Alaska; Resolute, Canada; and Tiksi, Russia. While previous studies have largely focused on cloud fraction, results will also be presented for cloud properties such as optical depth and phase since these variables have been shown to have a more direct effect on cloud radiative properties from studies conducted with SHEBA data.

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Using AVHRR Satellite Data to Investigate the Possible Effects of Dimethylsulfide Fluxes from a Coccolithophore Bloom on Regional Cloud Characteristics Over the SE Bering Sea

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Recent changes in the Bering Sea ecosystem have included large blooms of coccolithophores. Coccolithophores are known to produce significant quantities of dimethyl sulfide (DMS) which is released to the atmosphere. Atmospheric DMS oxidation products increase the number of cloud condensation nuclei (CCN), which can modify the droplet distributions in clouds, resulting in larger numbers of smaller-sized droplets and changes in cloud reflectivity, cloud lifetime, and precipitation frequency. Increased DMS concentrations over the Bering Sea thus could have a significant impact on the ecosystem through changes in the cloud cover and radiative fluxes.

We use the Cloud and Surface Parameter Retrieval (CASPR) software package (Key, 2002) to process five km AVHRR Polar Pathfinder (APP) data over the SE Bering Sea for the period April through October for the years 1993–2000 (covering pre- and post-coccolithophore bloom time periods). CASPR-derived variables include cloud and surface characteristics as well as short- and long-wave radiative fluxes at the surface and top of the atmosphere. Time series of variables obtained from CASPR including cloud effective droplet radius, channel 3 (3.7 mm) reflectance, cloud optical depth, columnar droplet concentration, and albedo will be presented.

Preliminary analysis of plots of the trend in cloud effective droplet radius, R_e, shows a decrease in the mean effective cloud droplet of 0.325 mm per year. The F-test showed that this trend is significant at the 95% confidence level. The trend starts at the beginning of the period being considered here, however, not in 1997 when the coccolithophore bloom began. The mean value of R_e for 1993–96 is 16.41 mm and that for 1997–2000 is 15.21 mm, a decrease of 7.3%. A similar decrease in R_e was also seen in clouds that had cloud top temperatures greater than 273 K (low-level liquid water clouds), but the decrease was not as large as that reported above. If our hypothesis is correct we would expect a decrease in R_e from the increased number of CCN due to the large flux of DMS from the coccolithophore bloom.

A positive trend in the channel 3 reflectance is also observed. The increase over the period is about 3% but the F-test showed that the trend was not significant. The trend, though, from 1995 to 2000, is highly significant and much larger. Future work will also include investigating the trends in the radiative fluxes.

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Development of Bias-Corrected Precipitation Database and Climatology for the Arctic Regions

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Precipitation is one of the key components in hydrological modeling and process studies. It is also the most important variable in global change analyses, as change of precipitation will have a major impact on hydrology, climate, and ecosystems. It has been recognized that significant (up to 100%) systematic errors (biases) exist in the gauge-measured precipitation records, and these biases must be documented and corrected in order to obtain a compatible, accurate data set for large-scale hydrological and climatic investigations.

The climate of the high latitudes is characterized by low temperature, generally low precipitation, and high winds. Because of the special condition in the high latitudes, the biases in precipitation gauge observations are enhanced and need special attention. This proposed research will directly address the problem of biases of precipitation measurements in the high-latitude regions. This work is based on the extensive research experiments, particularly on the WMO Solid Precipitation Measurement Intercomparison Project. We have evaluated and defined the accuracy of precipitation measurements, and implement the consistent bias-correction methodologies for the high latitude-regions (Alaska, northern Canada, Siberia, northern Europe, Greenland, and the Arctic Ocean). The goal of this research is to develop an unbiased and compatible precipitation database (including grid products) and climatology for the pan-Arctic.

This research is particularly relevant to studies of climate change and fresh water cycling in arctic regions, such as SEARCH and Arctic-CHAMP. It will collaborate with ongoing national and international efforts and develop value-added products. The results of this study will improve our understanding of the spatial and temporal variability of precipitation and its contribution to the freshwater balance of the high-latitude land and ocean systems. They will also be useful to analyses of global climate change and validation of the GCM/RCM.

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COASTAL PROCESSES: PRESENTATIONS

Missing Organic Carbon in the Coastal Kara Sea: Is Coastal Erosion a Significant Source?

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Studies of growth and respiration of heterotrophic bacteria in the southern Kara Sea have revealed depth-integrated carbon demand values barely matched by primary production. At the same time we found that the riverine dissolved organic matter is largely refractory to bacterial uptake, making only a minor contribution to the bacterial carbon demand. Due to the extreme seasonality of river discharge and our limited understanding of biological processes in the area it is not possible to come up with reliable carbon budgets. One of the missing pieces of information is the amount and character of particulate and dissolved organic carbon introduced to the system by coastal erosion. Organic matter trapped in permafrost is expected to be bioavailable and could contribute a significant amount of labile dissolved organic carbon to the Kara Sea system during the summer season. A focused study looking at the chemical composition and bioavailability of dissolved and particulate organic matter trapped along the coast would evaluate the fate of eroded materials in coastal arctic systems.

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Storm Patterns in the Circumpolar Coastal Regime Derived from Observational Data, 1950–2000

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The surface wind field climatology is an important component of many physical processes at the coastal margins, including wave and sea ice regimes. Knowing potential wind speed maxima and associated typical directions is a first stage in understanding and planning for contingency. Typically, the largest and most damaging winds are associated with storm events. We present results from analyses of fifty years of storm events extracted from wind speed data based on four-times-daily observational sources gathered by weather stations situated in the circumpolar coastal regions. Analysis is broken down into seven regional sectors as defined by the Arctic Coastal Dynamics (ACD) project steering committee.

General storminess patterns indicate winter intensities are greater than those in summer, in terms of wind speeds, event durations, and event counts. These general patterns exhibit regional variability. Delineation of trends in storm event variables is difficult because of the low signal-to-noise ratio inherent when the number of events per year is small yet highly variable from year to year. Such trends or patterns as are evident will be reviewed.

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Land-Shelf Interactions: An Update on Science Planning for Arctic Nearshore and Coastal Zone Research

Lee W. Cooper University of Tennessee

The Land-Shelf Interactions (LSI) science plan was developed with broad research community involvement over a three-year period with the goal of formally identifying critical research topics in arctic coastal regions (both nearshore and onshore) that need to be addressed in order to predict and respond to environmental change that is, or will be, significantly impacting human and biological communities. This science planning effort, sponsored by the National Science Foundation's Arctic System Science (ARCSS) program, has been largely completed, following a series of open workshops, on-line forums, comments on draft iterations of the science plan, and a collective editorial process that generated a "virtual" science plan that is available at http://arctic.bio.utk.edu/RAISE/index.html.

Among the key research topics that have been identified as needing emphasis are such unresolved issues as the impacts of dynamic changes on arctic coasts, including erosion, and the intermediate and ultimate fates of biogeochemical constituents provided to the coastal zone by rivers and as a result of shoreline retreat. The human dimensions of environmental change have also been recognized as having importance, including changes in subsistence gathering activities that are likely with changes in climate, sea ice regimes, and biological communities.

Within the context of SEARCH and its programmatic ties to internationally coordinated research efforts, the LSI initiative has incorporated international information sharing and coordination. LSI is an outgrowth of the Russian-American Initiative for Land-Shelf Environments (RAISE) research framework, which is the only bi-national science program jointly supported by both the U.S. National Science Foundation (NSF) and the Russian Foundation for Basic Research. Information about the potential research topics that could be supported through LSI and linked to internationally coordinated efforts have also been shared with research programs such as Land-Ocean Interactions in the Russian Arctic (LOIRA) and Arctic Coastal Dynamics (ACD), as well as international coordinating groups such as the International Arctic Science Committee (IASC) through its International Science Initiative in the Russian Arctic (ISIRA) and the International Geosphere-Biosphere Programme (IGBP) through its Land-Ocean Interactions in the Coastal Zone (LOICZ) program.

Following presentations at ARCSS Committee meetings in October 2002 and March 2003, the LSI science priorities are being formally considered as components of a new science announcement of opportunity that is expected to be recommended to the Office of Polar Programs at NSF by the ARCSS Committee.

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International Polar Year 2007–08: The Coastal Component

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The year 2007–08 will mark the 125th anniversary of the First International Polar Year (1882–83), the 75th anniversary of the Second Polar Year (1932–33), and the 50th anniversary of the International Geophysical Year (1957–58). The IPYs and IGY were important initiatives that resulted in significant new insights into global processes and led to decades of invaluable polar research. But in spite of the substantial effort in polar exploration and research over the years, both by individual nations and through international programs, the relative inaccessibility and challenging environment have left these regions less explored and studied than other key regions of the planet. Earth system processes in the polar region remain significantly less understood relative to our understanding of processes in other, more accessible regions.

Planning is underway to hold an International Polar Year (IPY) in 2007–08. It is envisioned as an intense program of internationally coordinated polar observations, exploration, and analysis, with strong education and outreach components. To be successful, IPY should be visionary and more than a continuation of present efforts (although current and planned efforts and enabling technologies should be part of what is done). It must address both the Arctic and Antarctic, and look for linkages between the regions. It must be multi-disciplinary, including study of human dimensions, and truly international. Ideally, IPY will provide both specific short-term outcomes and lay a foundation for longer-term commitments. If done well, IPY could attract and develop a new generation of polar scientists.

The International Council on Science (ICSU) has endorsed the IPY concept and has encouraged nations to determine their priorities. An ICSU Planning Group is preparing a draft science plan for distribution in February 2004. Thus this is an important time for the science community to articulate its interests. This presentation will outline current ideas for the next IPY, with a specific emphasis on projects related to the coast. The objective is to inform participants of current plans and gather input on other ideas and programs that could be integrated into the next IPY.

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The Role of Sea Ice in Arctic Coastal Dynamics and Nearshore Processes

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The arctic coastal zone is strongly affected by climate variability and environmental change, with important consequences for marine and terrestrial ecology, coastal infrastructure, and transfer of dissolved and particulate matter from the terrestrial permafrost regime into the marine system. Sea ice plays a key role in mediating and amplifying such environmental changes in the coastal regions. Relevant processes include but are not limited to 1) increased coastline exposure to wave action during summer and fall storms with a receding ice edge, 2) sea-ice entrainment and export of sediments in shallow water environments, 3) direct interaction between sea ice and the seafloor and coastline through gouging and ice push events, 4) impacts of bottom freezing on heat transfer into and out of the submarine permafrost layer, 5) larger-scale land-ocean heat and moisture exchange. While the importance of these processes is generally acknowledged, it is currently not at all clear how they quantitatively impact coastal dynamics and nearshore processes, either individually or in concert.

Here, we report on ongoing studies in northern Alaska that are of relevance in this context and could help in developing and refining future research on the role of sea ice for coastal and nearshore processes. On the regional scale, the northward retreat of the summer minimum ice edge in the Chukchi and

Beaufort Seas and the lengthening of the open water season during the past decade have had a substantial impact on coastal processes, ranging from increased wave heights and exposure, to fall storms, to impacts on seabird colonies. These processes play an important role in the evolution of coastal lagoons such as Elson Lagoon at Barrow, which has experienced rapid coastal retreat on the order of 0.5 to 2.5 m/yr. Changes in the open-water season are correlated with variations in the large-scale atmospheric circulation patterns (e.g., as expressed in the AO index). In the coastal zone, however, sea ice changes are more complex and their impact on coastal processes is more difficult to evaluate. Analysis of satellite imagery and onshore studies at Barrow, Alaska, indicates that in addition to changes in the length of the ice season, intra-annual variability in the stability and morphology of the fast-ice cover has substantially increased. In recent years, apart from a thinning of the ice cover, winter and spring landfast ice break-out events have increased, with substantial impacts on ocean-land heat transfer and local subsistence activities. Changes in sea ice cover are also impacting subsistence hunting activities in Bering Strait communities. Observations of substantial entrainment and export of sediment by sea ice further raise the question of whether ice-mediated removal of fine-grained sediments from the shallow shelf may be increasing in importance. For example, comparatively large inventories of ^{137}cesium, a bomb-fallout radionuclide associated with fine clay particles, and deposited over the past half-century on the continental shelf, are present in slope, submarine canyon, and deep basin sediments close to the continental slope. Changes in sea ice regimes are likely to have other consequences on biogeochemical cycling of biologically important materials in surface arctic waters, affecting productivity and the rates of transfer.

The characteristic time scales of these processes vary from days to decades, resulting in a complex response of this coupled coastal system to changes in the forcing. We will discuss how activities under the umbrella of SEARCH and other international projects could help in unraveling this puzzle.

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Coastal Erosion Along the Alaskan Beaufort Sea Coast and Regional Estimates of Carbon Yields

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The Arctic Coastal Dynamics program has established a methodology for estimating organic and sediment fluxes from coastal erosion of the circum-arctic seas. Rapid erosion of ice-rich permafrost is a major contributor to these fluxes. A regional classification of shoreline segments along the Alaskan Beaufort Sea Coast was developed as the basis for regional quantification of coastal morphology, lithology, and sediment characteristics.

We delineated forty-eight segments along the coast using the 1:250,000-scale World Vector Shoreline, which totaled 1,957 km of mainland coast and 1,334 km of spits and islands. We differentiated the mainland coasts into five broad classes: exposed bluffs (12 segments, 313 km), bays and inlets (6 segments, 235 km), lagoons with barrier islands (13 segments, 546 km), tapped basins (3 segments, 171 km), and deltas (14 segments, 691 km). Sediments of most segments are silts and sands, and uncommonly, gravel. Bank heights generally are 2–4 m high for most erosional areas and <1 m in depositional areas such as deltas. Mean annual erosion rates (MAER) by coastline type varied from 0.7 m/yr (maximum 10.4 m/yr at Elson Lagoon) for lagoons to 2.4 m/yr for segments along exposed bluffs (maximum 16.7 m/yr at Cape Halkett North Coast).

When considering dominant soil texture, MAER was much higher in silty soils (3.2/yr) than in sandy (1.2 m/yr) to gravelly (-0.3 m/yr) soils. Soil organic carbon stocks along eroding shorelines (excluding deltas) are estimated to range from 50 to 159 kg C/m^2 of bank surface down to the water line. When accounting for segregated and wedge ice, the mean annual carbon flux for eroding shorelines (1,265 km in 34 segments) is highly variable, ranging from 16 to 818 Mg (metric tons) C/km of shoreline. We assume carbon flux away from deltas is negligible because they are mainly depositional environments. Across the entire Alaskan Beaufort Sea coast, mean annual carbon input from eroding shorelines is estimated to be 149 Mg C/km of shoreline and total 1.7 x 10^5 Mg C/yr. Mean annual mineral input from eroding shorelines (deltas excluded) is estimated to be 2,743 Mg/km of shoreline and total 3.1 x 10^6 Mg/yr.

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Arctic Coastal Dynamics (ACD)—Status Report

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Coastal dynamics directly reflecting the complicated land-ocean interactions play an important role in the balance of sediments, organic carbon, and nutrients in the Arctic Basin. Recent studies indicate that sediment input to the arctic shelves resulting from erosion of ice-rich, permafrost-dominated coasts may be equal to or greater than input from rivers. Thus, the understanding and quantification of coastal processes is critical for interpreting the geological history of the arctic shelves. The predictions of future behavior of these coasts in response to climatic and sea level changes is an important issue because most of the human activity that occurs at high latitudes concentrates on the arctic coastlines.

Arctic Coastal Dynamics (ACD) is a multi-disciplinary, multi-national project of the International Arctic Science Committee (IASC) and the International Permafrost Association (IPA). Its overall objective is to improve our understanding of circum-arctic coastal dynamics as a function of environmental forcing, coastal geology and cryology, and morphodynamic behavior. In particular, ACD aims to:

- establish the rates and magnitudes of erosion and accumulation of arctic coasts;
- develop a network of long-term monitoring sites;
- identify and undertake focused research on critical processes;
- estimate the amount of sediments and organic carbon derived from coastal erosion;
- refine and apply an arctic coastal classification (includes ground ice, permafrost, geology etc.) in digital form (GIS format);
- extract and utilize existing information on relevant environmental forcing parameters (e.g. wind speed, sea level, fetch, sea ice etc.);
- produce a series of thematic and derived maps (e.g., coastal classification, ground ice, sensitivity etc.);
- develop empirical models to assess the sensitivity of arctic coasts to environmental variability and human impacts.

At the present state, emphasis is on developing a reliable circum-arctic estimate of sediment and organic carbon input from coastal erosion to the inner shelf, which involves classifying and segmenting the entire circum-arctic coastline into common elements based primarily on morphology, ground-ice composition, and erosion rates. During the third IASC-sponsored ACD workshop, held in Oslo, Norway, on 2–5 Dec. 2002, regional working groups continued previous efforts for their sectors, and the final version of the segmentation and classification will be available at the next ACD workshop to be organized in St. Petersburg, Russia, in November 2003. Additionally, representative photographs of coastal sites for each sector for inclusion in a coastal photo library available at the ACD web site (http://www.awi-potsdam.de/www-pot/geo/acd.html) were selected during the Oslo meeting. Finally, two circum-arctic working groups focused on GIS development and extraction and presentation of environmental data, respectively.

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Stable Carbon Isotopes in Sediments of the East Siberian Sea: Connection with the Long-Term Water Mass Transport

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The Arctic Ocean accounts for 20% of the world's continental shelves. The amount of terrestrial organic carbon stored in the wide circum-arctic shelf and slope areas is certainly of importance for calculation of organic carbon budgets on a global scale (Aagaard et al., 1999; Codispoti et al., 1990; Gobeil et al., 2001; Macdonald et al., 1998). More than 90% of all organic carbon burial occurs in sediment deposition on deltas, continental shelves, and upper continental slopes (Hedges et al., 1999), and the significant portion of organic carbon withdrawal occurs over the Siberian shelf (Bauch et al., 2000, Fahl and Stein, 1999).

The arctic coastal zone plays a significant role in the regional budget of carbon transport, accumulation, transformation, and seaward export. Hydrochemical anomalies obtained over the shallow Siberian shelves demonstrate a significant role of coastal erosion in the formation of the biogeochemical regime in the arctic seas (Semiletov, 1999) that could affect a hydrochemical regime of the surface and halocline waters over the Arctic Basin.

Determining the magnitude of particulate and dissolved fluxes of old organic carbon and other terrestrial material from land is critical to constraining a range of issues in the arctic shelf-basin system, including carbon cycling, the health of the ecosystem, and interpretation of sediment records. Most of the eroded terrestrial organic matter accumulates in coastal zones; however, significant amounts of this material are transported farther offshore by different processes, such as sea ice, ocean currents, and turbidity currents. The role of the coastal zone in transport and fate of terrestrial organic carbon has not been discussed sufficiently.

In this report we present new data about the distribution of organic carbon (^{13}C) and nitrogen (^{15}N) isotope ratios, OC/N, mineralogy, and size distribution of the surface sediment in the most unexplored area of the Arctic Ocean: the East Siberian Sea, the widest and most shallow shelf in the World Ocean.

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Coastal Processes and Climate Change Along the Canadian Beaufort Sea

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Coastal processes occur at the interface between ocean, atmosphere, and land. Oceanographic forcing in the form of waves, currents, and water levels interacts with seabed and terrestrial materials, modifying coastal morphology. Winds drive the waves and water levels, whereas air temperatures affect the cryological conditions both on land and in the sea. Coastal processes occurring at high latitudes differ fundamentally from those at temperate latitudes because of the presence of ice (both ground ice and sea ice) and permafrost. Sea ice mediates the interaction between atmosphere and ocean, affecting wave generation and storm surges and impacts nearshore sediment transport and coastal permafrost stability. The presence of ground ice and permafrost control the initial strength of coastal materials and ice content affects the nearshore sediment budget and local morphological conditions.

Over the past ten years, coastal research in the Canadian Beaufort Sea has focused on improving our understanding of the relations between the unique aspects of high-latitude environmental forcing and coastal impacts. Coastal processes in the region tend to be storm-dominated and occur during the short open-water season. Analysis of coastal meteorological and sea ice records have identified a high degree of inter-annual variability, but no apparent trends in storminess or open-water-season sea ice extent. However, there is an indication that open-water extent just prior to freezeup is increasing. Tide gauge records indicate that relative sea level is rising at rates of up to 3.5 mm per year as a result of the combination of subsidence and eustatic sea level rise. The relative importance of the former is critical in order to estimate impacts resulting from predicted acceleration of the latter. Co-located tide gauges and global positioning systems have been installed in several locations in the Canadian Arctic in order to determine absolute rates of sea level change, by direct measurement of vertical motion and relative sea level.

Coastal change rates have been measured using a combination of ground surveys, marine surveys, and remote sensing methods. Mechanisms of subaerial coastal change (e.g., retrogressive thaw failure and thermal notching) affect retreat rate measurements by causing lag effects between storm events and removal of erosion products. The coastal change rates show a high degree of both temporal and spatial variability with differences of more than an order of magnitude in successive years and between adjacent coastal reaches. To date, no trends in rates of change have been observed. It is noteworthy that rates of coastal change do not appear to be substantially affected by sea ice conditions. This is because wind-generated waves and storm surges are limited as much or more by local morphological conditions (e.g., water depth and coastline shape and exposure) than by fetch limitations imposed by sea ice. Therefore, predicted changes in sea ice extent are likely to be less important than changes in the length of the open-water season. Extension of the open-water season into the fall will increase the probability of occurrence of high-magnitude storm events when the coast is vulnerable. Ground ice content is a locally important determinant of coastal change rates, especially where sediment supplies are already limited and ground ice is close to or below mean sea level.

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Coastal Erosion and Nutrient Balance of the Arctic

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Siberian Russia belongs mainly to the Arctic Basin. Natural processes, including alterations in climate and vegetation disturbances, drive the environmental changes in this huge area. This territory is sparsely populated and sporadically used for mining minerals, oil, and gas. Most of the territory has a mean annual temperature that is below 4–6^{o} C, which coincides with the zone of sporadic and continuous permafrost. In spite of the projected warming in the future, climate conditions in the region remain too severe for agriculture, and current land use is not expected to change.

Climate warming is thought to affect the permafrost and stimulate thermal abrasion of the coastal zone. It is reported that on a global average nearly 85% of marine organic carbon (C) originates from the photosynthetic activity of phytoplankton; the remaining 15% comes from the land (Artemyev, 1996). A lot of observations have been done on the riverine discharge in Russia (Vinogradov et al., 1998; Romankevitch and Vetrov, 2001). The latest investigations have found that due to intensive thermal abrasion, coastal sediment input into the Arctic is larger than globally observed and even exceeds that of rivers (MacDonald et al., 1998; Rachold et al., 2000). These observations contribute to understanding the marine biology of Russia's arctic seas, e.g., relatively low biological activity and limited fish resources. However, to assess the effect of thermal abrasion a better knowledge of the biogeochemical land-ocean interactions and coastal environment is needed.

The overall goal of the study is to describe the biogeochemical cycle of the coastal ecosystems along the Eurasian coastline and to estimate the possible nutrient flux in the Arctic from coastal erosion. The study is mainly based on data from the CD-ROM "Land Resources of Russia" (Stolbovoi and McCallum, 2002). Among numerous land characteristics the latter contains spatially explicit databases on soils and their chemical composition, vegetation, and C content in the phytomass fractions. Data on the nitrogen content in vegetation and hydrochemistry of river transport is derived from a literature search.

The length of Russia's segment of the arctic coastline is approximately 40,000 km. Various subzones of the tundra dominate along this line, e.g., polar (13%), arctic (24%), northern (14%), and southern (16%). However, bogs (6%), northern taiga (5%), and halophytic meadows (3%) are insignificant. The C density in phytomass of the coastal ecosystems varies from 0.65 kg m^{-2} (average for the tundra) to 1.87 kg m^{-2} (average for forest tundra and northern taiga). The most widespread soils (30%) are histosols (international FAO nomenclature) with shallow peat (about 0.3–0.5 m), and histosols with deep peat (more than 0.5 m) occupy about 6% of the coastal zone. Histic gleysols represent about 30% of the zone, whereas coarse textured podzols (15%), and histic fluvisols (10%) play a minor role. The share of calcaric soil units is considerably less than 1%. The effective soil depth is about 0.5 m and is limited by shallow groundwater, hard rock, and permafrost. The average organic C density for topsoil (0.3 m) of the tundra biome is about 12 kg m^{-2}; the forest-tundra and northern taiga comprise about 13 kg m^{-2} (Stolbovoi, 2002). The concentration of organic C in the topsoil of the coastal zone is much higher due to the dominance of histosols (21 kg m^{-2}) and gleysols (18 kg m^{-2}). The organic content in the topsoil of excessively drained podzols is 6.7 kg m^{-2}. The formation of the histic horizon in the coastal zone soil is caused by cold climate, waterlogging, deteriorated decomposition rate and the quality of vegetation residues in recalcitrant compounds (moss, lichen, vascular plants, etc.). The total ecosystem C content (soil depth 0.5 m) in the coastal zone is approximately 10–12 kg m^{-2} for well-drained and 35–40 kg m^{-2} for poorly drained sites. The segments along the coastline have very different soil-vegetation associations depending on the height above sea level, texture and mineralogy of parent materials, depth to ground water, permafrost, etc.

The littoral deposits contain some 3.8 million tons (about 1%) of organic and 4–5 million tons (about 1.5%) of inorganic C. These concentrations of C do not match the above-mentioned organic C pools of the coastal ecosystems that are subjected to degradation. Clearly, processes of coastal sea erosion are different from that of the terrain due to the excessive amount of water. The latter causes the separation of C substances on heavy and light weighted fractions. The heavy weighted fraction tends to deposit in the littoral zone, which comprises mainly minerals, including carbonates relatively accumulated in the sediments and some organo-mineral compounds. The latter are not common for permafrost-affected soils with a limited humification rate. This explains the relatively low concentration of organic C in the sediments. The light weighted fraction contains vegetation fresh tissues, raw undecomposed residues, peat, etc., and floats on the surface of the sea. This fraction comprises up to 99% of the C pool of coastal ecosystems and is transported out of the coastal zone.

The contribution of shore abrasion to the organic C flux from the Eurasian continent to the Arctic Basin comprises about 20–25% (4–5 x 106 t a^{-1}) of river transport (about 23 x 106 t a^{-1}, Vinogradov et al., 1999). These data illustrate a relatively higher contribution of the coastal zone to the C balance of the Arctic. However, this role would be considerably more significant if the transport of the other essential nutrients was considered. As noted above, the materials delivered by coastal erosion consist mostly of the products of destruction of terrestrial ecosystems of the onshore zone, e.g., living vegetation and its dead residues, underdercomposed peat, soil humus, etc. These products are highly biologically active. For example, the concentration of nitrogen in organic matter transported by rivers is 2–3 times less than that of soil organic horizons and vegetation. Taking this difference into account, we estimate that by contributing about 20–25% of C of the riverine discharge, the coastal erosion supplies nearly half of the organic nitrogen. Clearly, degradation of the huge amount of low molecular weighted fresh and undecomposed organic matter derived by coastal erosion requires a considerable amount of oxygen and seriously affects nutrient budgets by releasing dissolved ions of nitrogen and phosphorus. The input of undecomposed substances supports formation of anoxic water within the estuarine zone in which the bacterial activity and chemical processes drastically modify the speciation of some nutrients. All of the above-mentioned play a principal role in ocean biogeochemistry and biology, which is poorly understood at present.

Conclusions: 1) climate change is expected to accelerate the thermal abrasion of the Russian arctic coast and will increase the transportation of vegetation residues and underdecomposed organic matter of soils with a high nutrient content; 2) the scenario is that an intensification of the supply of undecomposed organic matter might increase the extent of anoxic water and deplete the biological activity in the ocean; and 3) the dynamics of the coast and associated ecosystems should be better understood so as to assess the magnitude of a possible change in the Arctic.

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Hydrological and Morphological Processes in the Arctic River Deltas: The Yana and Indigirka Rivers, Russia

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Comprehensive analysis of hydrological regime and hydromorphological processes of the Lower Yana and Indigirka Rivers as well as their features in the far northern environment are described. Channel processes, conditions of forming and transformation of water runoff and sediment load in the subdelta section, their distribution amidst delta channels, processes of delta development, and penetration of sea water upstream river channels are the focus of the research. All results are based on long-term network observations and fieldwork. Problems concerning the ecological aspects of delta channel regulation and dredging of mouth bars are considered.

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Contributions to Quaternary and Recent History of the Bering Sea Coast of Kamchatka, Russian Far East

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This cooperative interdisciplinary project is currently funded principally by NSF (EAR/INT), as well as by the Russian Foundation for Basic Research. Funded objectives include 1) Holocene volcanic history (tephra stratigraphy) of northern Kamchatka, both on its own scientific merit, and also as a tool for dating and correlation in other aspects of the project; 2) Holocene paleoseismology of eastern Kamchatka, especially history of earthquakes and tsunamis in this region; 3) Quaternary shoreline and sea level history of Kamchatka, including progradation (beach ridge history) and erosion, subsidence, and uplift (terrace history). Auxiliary work (currently minimally funded) includes Holocene palynology and peat macrofossil studies, and diatom studies. Potential applications range from natural hazard analysis to archaeology.

The southern Bering Sea coast of Kamchatka is tectonically active (undergoing uplift and deformation) and lies at a major plate boundary—the northern terminus of the Kuril-Kamchatka subduction zone. Volcanic ash layers from the very active Kamchatka volcanic chain permit widespread correlation and age control for the Holocene. Kamchatka probably has the best established Holocene tephra stratigraphy in the world, and we are working on a database for these tephra. Our key study sites are coastal peats; in this part of Kamchatka, we have found coastal peats as old as about 8,000 years which preserve a record of land-level changes, vegetation history, volcanic eruptions, tsunamis, and storms. Our methods also include measuring and description of coastal profiles and environments, so we are documenting current conditions at many sites along the Kamchatka Bering Sea coast. These surveys give us a baseline for reconstructing the past and for projecting future change.

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Toward a Holocene Sediment Budget of the Central Kara Sea Shelf

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High-resolution acoustic data and several sediment gravity cores taken in the Ob and Yenisei estuaries and the central Kara Sea shelf allow us to balance the Holocene sediment budget of the central Kara Sea shelf and to reconstruct the sedimentary history. Cores were radiocarbon dated and linked to acoustic profiles using whole-core physical properties.

The Ob and Yenisei estuaries, with their sea water/freshwater mixing zone, act as major sediment sinks for fluvial-derived terrigeneous material in Holocene times. Most of the suspended and large amounts of dissolved matter precipitate in this zone termed "marginal filter." High thickness of Holocene sediments occurs between 72°N and 73°30'N where a distinct decrease in thickness is observed to the north. Two major acoustic units could be differentiated, separated by a prominent reflector interpreted as the base of the Holocene. High-resolution echosound data suggest a fluvial-dominated depositional environment for the early Holocene, displaying lateral accretion as point bars and vertical accreted overbank deposits in a fluvial channel-levee complex. During the early Holocene sea-level rise the marginal filter migrated progressively southward (upstream) to its present position, forming a typical high-stand system tract in acoustic images. Estuarine sedimentation in a sedimentary environment similar to today's, started at approximately 5 cal. kyrs. B.P. An estimated total of 14.3 * 1010 t and 9.2 * 1010 t of fine-grained brackish-marine sediments, in the Ob and Yenisei estuaries, respectively, were accumulated during Holocene times. This is only about 75% and about 50% of Ob and Yenisei estuarine sediment budgets, respectively, estimated by extrapolation of recent river runoff data over the past 7,500 years. Filled paleoriver channels indicate active river incision in the southern part of the Kara Sea shelf prior to the Holocene.

New Parasound data obtained during the recent (2003) cruise of RV *Boris Petrov* and the interpretation of the existing data allow a first estimate of Holocene sediment volume deposited on the Kara Sea shelf.

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Advection of Carbon on the Western Arctic Shelf: Implications for Benthic-Pelagic Coupling

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Our recent work addresses the linkages between benthic community structure and biomass in the western Arctic to associated physical and biological processes. Patterns in benthic biomass reveal distinguishing features that are related to the northward flow of organically rich waters that pass through the Bering Strait and then split, with part of the water flowing northwest to the East Siberian Sea and the other part moving northeast through Barrow Canyon and to the Beaufort Sea. Evidence for the importance of rich Bering Sea waters on the Arctic Shelf is provided by carbon and nitrogen stable isotope signatures to trace carbon advected onto adjacent shelves and as indicators of trophic links between pelagic and benthic components of the shelf and slope. Our preliminary d^{13}C measurements of POM reveal that d^{13}C values are 2–5 ‰ lower (more negative) in late summer compared to spring, especially over the shelf and basin. Based on these results and the isotopic values of ice algae, we estimate that ice algal carbon potentially contributes up to 25% of the POC pool over the Chukchi Shelf during the spring bloom.

Overall, benthic organisms become more ^{13}C depleted between the Chukchi Sea and western Beaufort, while ^{15}N ratios remain relatively constant. These data support the hypothesis that carbon advected northeastward along the Alaskan arctic coast is assimilated by benthic consumers, but its relative importance begins to decline east of Point Barrow. We plan to better define the significance of carbon advected northward onto adjacent arctic shelves through the additional collection of POM and zooplankton along the Chukchi and Beaufort Sea coasts in summer 2003.

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Barrow Alaska: A Focal Point for Ice-Albedo-Transmission Feedback Studies of Arctic Sea Ice

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As detailed in the SEARCH science plan, the arctic sea ice cover has measurably decreased in thickness, extent, and seasonal duration over the past two decades. This has culminated in record or near-record fluctuations in 1998 and again in 2002 followed by a further strong melt season in 2003. Of central importance in this context are seasonal changes and short-term variability in the state of the ice cover and their effect on the interaction of solar radiation with the ice and underlying ocean. Positive feedback processes associated with decreases in albedo and increasing transmissivity act to accelerate these changes. The rates of spring warming and summer melt as well as the length of the melt season are strongly influenced by the albedo, which in turn decreases as the melt season progresses. At the same time, increased transmission provides more energy to the upper oceanic mixed layer further increasing the potential for melting at the bottom of the ice. This ice-albedo-transmission feedback plays a central role in modulating the heat and mass balance of the arctic sea ice cover, and its effects are strongest at the ice margins where albedo contrasts are greatest. Along the coastal contact zone, the feedback processes are particularly complex due to interactions with the adjacent land surfaces. Indeed, this zone is where the summer melt is initiated and is a focal point where the feedbacks are amplified.

To understand and model the processes involved, it is necessary to determine how shortwave radiation is distributed within the ice-ocean system and how this distribution affects heat and mass balance. Analysis of this system is complicated by spatial and temporal inhomogeneity of the spring/summer ice cover, with surface conditions varying from deep snow to bare ice to melt ponds to open leads, and with ice thickness ranging from zero (open water) to ridges tens of meters thick, all within an area that is often less than one square km. Each of these categories has a different set of physical and optical properties. Treatment of the surface as a locally homogeneous medium with effective bulk optical properties represents a serious oversimplification that will significantly limit the predictive power of regional and large-scale climate and dynamics models. Understanding the evolution of melt ponds and the absorption and transmission of shortwave radiation by a heterogeneous ice cover have been identified as central problems but are among the least well understood processes involved. Since these are sub-grid scale processes with respect to GCM modeling, the most efficient approach to dealing with them is to carry out surface-based, process-oriented observations to determine the detailed spatial and temporal variability associated with the various surface types and develop appropriate models to apply this information on larger scales.

The coastal zone in the vicinity of Barrow, Alaska, is critically situated for studies of the processes described above. Results from a recently completed three-year observational study of heat and mass balance of the ice cover in conjunction with the interaction of solar radiation with the ice and adjacent tundra and lakes shows large lateral gradients in solar energy absorbed by the surface. This information is needed to make an accurate determination of partitioning of solar heating in this zone and provides the basis for ice-albedo feedback modeling. We will describe some modifications that will be important for generalizing to conditions attendant to increases in the length of the melt season. We propose that this type of study be continued as part of the SEARCH program and that Barrow is an area ideally suited for these types of measurements. It offers a key scientific location in combination with superior logistics support and extensive opportunities for K–12 outreach and support of higher education.

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Geological and Geophysical Research into the Impact of Earthquakes on Prehistoric Coastal Occupation: the Mid-Holocene Occupation and Abandonment of the Tanginak Spring Site

Elizabeth Mahrt University of Washington[1], **Bretwood Higman** University of Washington[2], **Joseph MacGregor** University of Washington[3], **Joanne Bourgeois** University of Washington[4], **Ben Fitzhugh** University of Washington[5]

Student Poster

Since their earliest arrival, humans living on the tectonically active subarctic coastal margins of the northern Pacific have had to adapt to both gradual and rapid environmental changes. The research reported here documents the effects of dynamic geological processes on the settlement history of an ancient archaeological site on the Kodiak Archipelago, Alaska. The Tanginak Spring Site on Sitkalidak Island was occupied from 7,500 B.P. until it was permanently abandoned about 6,000 B.P. We conducted geological and geophysical analyses of the surrounding area in order to elucidate environmental conditions which existed during the occupation and abandonment of this site. Volcanic ash layers permit correlation amongst the archaeological and geological sites. Our investigations suggest that during the period of occupation the area was experiencing gradual sea level rise, followed by an earthquake with associated uplift and tsunami at the time of abandonment.

The Tanginak Spring site is situated on an 8-m-tall bench above a salt marsh protected from the ocean by a series of beach ridges. We examined beach-ridge history with ground-penetrating radar as well as with some trenching. Near the salt marsh are hills bounding small peat bogs at varying elevations recording tephra and peat accumulations since deglaciation. We excavated, described, and sampled multiple excavations in the salt-marsh and freshwater peats in order to reconstruct environmental history before, during, and after Tanginak site occupation. Evidence for abrupt sea-level change (uplift) at or near the end of occupation includes: peat overlying beach deposits; sharp peat facies changes, and tsunami deposits implying co-seismic deformation.

The geology near the Tanginak Spring Site provides a basis for understanding why this site was occupied and abandoned. During occupation, sea level rise prevented a lagoon below the site from infilling and also rendered locations closer to sea level vulnerable to erosion and storms. The earthquake, that we postulate marked the end of occupation, was probably exceptionally damaging and followed within minutes by a large tsunami. Uplift associated with this earthquake permanently drained the harboring lagoon and left the new shoreline far from the site, leading to abandonment of the location.

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Long-Term Changes in Landfast Ice and Its Contribution to Shelf Freshwater

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Landfast ice plays a unique role in the land-upper ocean freshwater cycle. Formed in the shallow water along the arctic coasts, landfast ice can lock up a significant amount of freshwater from river discharge and ice melt, but most of this freshwater will be returned back to the shelves during summer melting. The freshwater stored in landfast ice is comparable to the total annual runoff of the four largest arctic rivers.

The growth and melt of fast ice displays a large interannual variability. Of climatic significance are the year-to-year changes in the storage and the timing of the released fresh water. Recent observations indicate some substantial changes in the arctic climate. These changes may affect the freshwater exchange between the land and the upper ocean, partly through altering the growth and melting patterns of landfast ice.

Under the Arctic Freshwater Initiative funded by NSF, this research examines the long-term changes in landfast ice and its contribution to the arctic freshwater budget. By modeling fast ice thickness and integrating these results with a twenty-six-year record of landfast ice extent observation, this study analyzes the basin-wide changes in landfast ice cover, including ice extent, growth/melt, and freshwater storage. To relate the results to the arctic climate variability, the changes in fast ice will be compared with different arctic climate variables.

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SOCIAL FEEDBACKS: PRESENTATIONS

ArcticNet: The Integrated Natural/Health/Social Study of the Changing Coastal Canadian Arctic

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With funding starting in 2003, ArcticNet is a new Canadian Network of Centres of Excellence that will build synergy among existing arctic Centres of excellence in the natural, medical, and social sciences. The central objective of the Network is to translate our growing understanding of the changing Arctic into impact assessments, national policies, and adaptation strategies. The Network is built around the new Canadian research icebreaker that will help solve the present want of observations and data for the Canadian Arctic by providing Canadian oceanographers, terrestrial ecologists, geologists, epidemiologists and their international partners with unprecedented access to their study area. Over the next four years and beyond, ArcticNet will conduct Integrated Regional Impact Studies (IRIS) of the coastal marine Canadian high Arctic (Theme 1); the terrestrial ecosystems of the eastern Arctic (Theme 2); and Hudson Bay (Theme 3). Each of these IRIS will contribute the knowledge needed to formulate policies and adaptation strategies for the Canadian coastal Arctic (Theme 4), that address the following concerns of users: the rate of change of the arctic environment; reducing human vulnerability to hazardous events; adapting the public health system to change; protecting key animal species; maritime transport in an ice-free Canadian Arctic; and the economic impacts of environmental change in the Arctic.

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Climate System-Social System Interactions in the Northern Atlantic

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Large-scale environmental changes involving the North Atlantic Oscillation (NAO) and arctic-origin Great Salinity Anomalies (GSAs) have affected fisheries-dependent societies across the northern Atlantic in recent decades. Recurrent themes appear in many of these stories.

- Time plots show spikes of overfishing followed by steep declines, sometimes becoming a multi-decade collapse.
- Declines commonly involve interactions between fishing pressure and environmental variations associated with the NAO and/or GSAs.
- Fisheries adapt to the loss of traditional resources, where possible, by shifting efforts to target a wider range of species, particularly crustaceans, which become more abundant as bony fish grow scarce.
- For ecological as well as economic reasons, the new fisheries tend to be more capital-intensive and less labor-intensive compared with the old.
- As ecosystems and fisheries change, there are winners and losers on land.
- Many small communities experience selective outmigration and demographic change.
- Social factors influence the differential outcomes among people and communities.

Illustrations of such ecosystem-society interactions are drawn from recent case studies of fisheries-dependent regions in Newfoundland, Greenland, Iceland, and the Faroe Islands. Common elements from these case studies suggest general patterns in the human dimensions of large-scale environmental change.

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Detecting Change Through Community-Based Ecological Monitoring: Successful Examples of Systematic Local Knowledge Observation Systems

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Local knowledge, documented through the systematic and ongoing contributions of community-based ecological monitoring, has enormous potential to contribute to the goals of SEARCH, and in particular, its Detecting Change component. As well, it offers a workable approach for involving local communities in this area of study.

This paper explores the potential contributions of local knowledge to SEARCH by presenting examples of several established and ongoing community-based observation systems of Alaska and the Canadian Arctic. Highlighted here is the Arctic Borderlands Ecological Knowledge Co-op, a low-cost collaborative alliance of indigenous communities, government agencies, co-management boards, and university researchers, asking the question “What is changing and why?”

Since its creation in 1996 as a part of Canada’s EMAN program and expanding to include Alaska in 1998, the “Knowledge Co-op” has developed a new model for documenting local knowledge on change and effectively integrating it with the work of research science. Indicators are identified through a regional meeting involving players of a region. An instrument (questionnaire) is administered by locally hired residents of communities across a region. Qualitative, quantitative, and spatial data about weather conditions, berries, fish species, caribou, other animals, and changing community, social, and cultural conditions are documented annually through interviews with active subsistence harvesters. Data are compiled in a database that provides easy reporting of findings to communities and other interested parties. The Knowledge Co-op facilitates communication through use of the WWW for data access (www.

taiga.net/coop), an annual gathering for face-to-face discussions, and regularly published reports for review by the greater public. Community monitoring of this program complements other monitoring efforts of the region by addressing changes in the abundance and movement of animals, unusual sightings, short-term trends, societal responses and long-term changes at the local scale. Also part of the community monitoring program are explanations of change and traditional rules of thumb.

The Knowledge Co-op approach and other models of community monitoring have been highly successful in facilitating a conversation among community residents, resource managers, and researchers about change, in identifying data gaps and research questions, and in building trust among parties of a region. While various approaches to community based monitoring differ, all come with interesting challenges and opportunities for the SEARCH program.

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Shared Knowledge for Decision-Making on Environment and Health Issues in the Arctic

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This paper will describe a remote sensing and GIS-based system to bring indigenous traditional knowledge together with contemporary scientific knowledge to address impacts resulting from changes in climate, environment, weather, and pollution in the Arctic. As scientists and policy-makers from both indigenous and non-indigenous communities continue to build closer partnerships to address common sustainability issues such as the health impacts of climate change and anthropogenic activities, it becomes increasingly important to create shared information management systems which integrate all relevant factors for optimal information sharing and decision-making. This system is being designed to bring together remotely sensed, indigenous, and other data and observations for analysis, measuring, and monitoring parameters of interest (e.g., snow cover, rainfall, temperature, ice conditions, vegetation, infrastructure, fires). A description of the system and its components as well as a preliminary application of the system in the Arctic will be presented.

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The Influence of Environmental Conditions On the Success of Hunting Bowhead Whales Off Barrow, Alaska

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Analysis of the bowhead whale hunt at Barrow (1990–1997) suggests that hunting success is greatly influenced by wind direction and speed. During the spring hunt along the Chukchi Sea coast, hunters tell us that open leads, moderate to strong offshore winds (easterly component), and stable landfast ice are required to hunt and land whales successfully. This is mainly because easterly winds open lead systems at Barrow by pushing the pack ice offshore. Said another way, it is the presence or absence of sea ice in the nearshore lead that affects spring bowhead hunting success, and wind direction is a reliable indicator of lead conditions and ice cover within the lead. Bowhead whales are generally harvested in spring when winds are offshore (easterly) and are almost never taken when winds are onshore (westerly component). During the fall bowhead hunt offshore of Point Barrow (Beaufort and Chukchi Seas), calm to moderate winds and relatively ice free waters are required to hunt whales effectively. Wind direction, however, does not appear to affect fall hunting success, whereas wind speed has a significant effect. Selected seasons (i.e., spring 1992, 1993, and 1997 and fall 1997) were examined in detail to illustrate extremes in environmental conditions and to explore hunters' observations using quantitative Western scientific methods. This analysis does not formally include the various sociological aspects (e.g., numbers of active crews, cease-fire periods, festivals) of whale hunting which also affect success. Our findings suggest that the bowhead whale hunt at Barrow is highly affected by environmental conditions and that wind speed in the fall and wind direction and ice cover in the spring are the principal variables affecting whale-hunting success. Furthermore, our scientific findings all agree well with the hunters' predictions. Such variability in hunting conditions supports flexible hunting regulations that allow for hunting failures (due to environmental factors) during some seasons.

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Community-Defined Climate Change Impacts and Adaptation Research Needs in the Canadian North

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Understanding and adapting to the impacts of climate change in the North will require much new information and research. However, time and resources to conduct climate research are very limited, so research priorities need to be chosen carefully. Northern communities will need information to support decision-making on adaptation. To encourage the generation of this information, northern communities will benefit from specifying what information they require to support decisions, and communicating these information needs to the research community. To facilitate this interaction, the northern offices of the Canadian Climate Impacts and Adaptation Research Network (C-CIARN North) undertook a survey to identify research needs in communities in the three northern Canadian territories as part of a process to assist researchers and research funding bodies to establish priorities for future climate change impacts and research in the various regions of the North. This research-needs survey attempted to engage communities in answering an important question: what information and research do communities need, to address climate change impacts? Survey design was based on the results of the Northern Climate ExChange Gap Analysis Project (2002), which summarized what is known about the potential impacts of climate change in northern Canada according to sixteen natural, economic, and community systems. For each system, this project reviewed scientific, local, and traditional knowledge sources, and ranked the state of knowledge as good, fair, or poor, according to a common standard. Survey respondents were asked to help decide where we need to focus our collective efforts in filling knowledge gaps or improving the state of knowledge for each of these systems. It is hoped that the results of this survey will be used by researchers, research institutes, funding agencies, and other groups, to help design and promote research on climate change issues and themes that are important to Northerners and that will provide information useful to Northerners.

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Understanding Human and Ecosystem Dynamics in the Arctic: the Imandra Watershed Project (Kola, Russia)

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The Imandra Lake watershed is located in one of the most developed regions in the Arctic—the Kola Peninsula of Russia. There are approximately 300,000 people living on the roughly 27,000 square kilometer watershed, making it one of the most densely populated areas of the Arctic. Most of the people are involved in large-scale mineral extraction and processing and the infrastructure needed to support this industry. A US-Russian research effort has been started for the Imandra Lake watershed that has put human dynamics within the framework of ecosystem change to integrate available information. The observation period is one of both rapid economic growth and human expansion, and a period of overall economic decline in the past decade. We are applying the Participatory Integrated Assessment (PIA) approach to bridge the information gaps and link scientific findings to the decision making process. Incorporating information on the vastly perturbed ecosystem, we are observing an increasingly vulnerable human population in varying states of awareness about their local environment and fully cognizant of their economic troubles, with many determined to attempt maintenance of relatively high densities in the near future even as many residents of northern Russia migrate south. Based on this information, a set of likely development scenarios for further analysis has been derived. Thus far, a series of workshops have involved the citizens and local decision makers in an attempt to tap their knowledge of the region, and to increase their awareness about the linkages between the socio-economic and ecological components. A hierarchy of qualitative and quantitative models is under development for use in understanding the complex integrated processes in the watershed, structuring the available data sets, and outlining potential scenarios.

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SOCIAL FEEDBACKS: POSTERS

Resilience to Hydrologic and Climate Change on Human Communities in the Arctic: Quantifying the Linkages Between Social and Ecological Systems

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Arctic communities have always striven to adapt to changing physical, biological, social, and cultural environments. Accordingly, they offer guidance in understanding how human communities perceive, articulate and make operational their biophysical environment. We will investigate how community resilience is generated and winnowed by differing perceptions, and resultant responses to change in local social-ecological systems (SESs). To do so, we will identify components of resilience and metrics to quantify it.

Climate models at local scales lack enough data on human behavioral responses to change to accurately predict feedbacks, and hence consequences, between socio-cultural and biophysical systems. The inherent interaction between biotic and abiotic components of social-ecological systems through the flow of information suggests that some primary drivers of resilience may be found in the field of human cognition. We take an interdisciplinary approach that quantitatively assesses people's perceptions of their SES, and the mechanisms by which these perceptions create values and drive behaviors. We incorporate scale as a critical element, assessing spatial, temporal, and institutional elements. We then use modified components of ecological "optimal foraging theory " to provide a mathematical framework for articulating our quantitative data within a cogent scientific theory. This analysis will be the basis for the subsequent programming of intelligent agents in Boolean models (a collaborative project with Complex System mathematicians at the University of Alaska, Anchorage). This provides a means to incorporate cognitive and realized elements of risk and reward over a broad suite of benefit categories. We can then use scenario testing and model outputs to better understand the epistemology of human responses to SES change, both optimal and sub-optimal. These data will enable more adaptive, encompassing, and precise models of human responses to climate change to be generated and applied to diverse SESs.

We work closely with a parallel CHAMP project (White, Alessa, Hinzman, and Schweitzer) to assess human perceptions of, dependences on, and responses to potential change in water resources. This project fully integrates community participation, education, and desired future-states into a transparent quantitative framework, which is both accessible and applicable.

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Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model

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Climate warming could affect abundance, distribution, and access to wildlife that arctic communities harvest for subsistence. Another set of global forces increasingly directs local cash economies that support the logistics of subsistence activities as well as providing market consumption goods. Agent-based computational models may contribute to an integrated assessment of community sustainability by simulating how people interact with each other and adapt to changing economic and environmental conditions.

Relying on local knowledge to provide qualitative rules for individual and collective decision-making and to estimate parameter values where other data are unavailable, the model generates hypothetical futures as adaptations to scenario-driven changes in environmental and economic conditions. The model projects wage employment, cash income, subsistence harvests, and demographic change over four decades based on a set of user-defined scenarios for climate change, development, and government spending. Simulated outcomes for one Canadian arctic community—Old Crow, Yukon Territory—assess how potential adverse economic events or a warmer climate (or both occurring at once) might affect the local economy, resources harvests, and the well-being of residents.

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Human Dimensions of Climate Change at the Bering Strait Environmental Observatory

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The major goal of the Bering Strait Environmental Observatory is to improve environmental observation capabilities in the Bering Strait region. In this sparsely populated, remote area adjacent to the Russian-U.S. boundary, local residents are heavily dependent upon subsistence food resources, and they are keenly aware that changing weather, sea ice regimes, and biological cycles can have major impacts upon the viability of long-established human communities.

In particular, at Little Diomede Island, where we have been working to establish continuous water sampling capabilities and have cooperated with local hunters to obtain marine mammal tissues for scientific analyses from animals harvested for consumption, we could not successfully undertake any significant research without support from the local community and school. We provide information here on our research activities since 2000 that have benefited from the local community's interaction and the extent of the local community's interest in the results of our work.

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Climate Change and Inuit Health: Impacts and Adaptation in the Canadian North

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There is a growing concern among Canadian Inuit about the impacts on environment, health, and culture from global changes such as climate change. To date, the focus on this subject has been oriented toward biophysical changes and impacts in the environment and little attention had been given to the potential impacts on public health in northern communities. In response to interest by northern communities and organizations, a project and series of community workshops investigating climate change, potential impacts, and strategies for adaptation was initiated in Canadian Inuit regions. The projects reviewed scientific and traditional knowledge documentation, conducted focus group discussions and interviews with Inuit in three regions, and convened seven workshops involving residents of eleven Inuit communities. Through these activities, a number of direct and indirect climate related impacts on Inuit health were identified; Inuit observations on changes in the regions and their perspectives on the relationship between these changes and their health were gathered; and existing and potential community responses to changes resulting in adverse community impacts were documented. Climate change in Inuit regions poses health risks related to increased heat and cold stress, increased exposure to UV-B radiation, safety while traveling or pursuing hunting and fishing activities because of changes in weather and storm events or stability and safety of ice and snow, impacts to food security related to access and availability of important traditional food species, the potential introduction of new vector-borne or water-borne diseases, as well as impacts to critical health infrastructure related to altered permafrost stability in communities. In many cases, communities in the Canadian North have already started to cope and adapt to changes occurring in their local area. Community workshops have identified communities where hunting and fishing patterns have been altered, significant investments in shoreline protection programs have taken place, where water consumption habits have changed, and in many cases, where further programs for adaptation are needed. This project has provided the impetus for further work in these communities and regions related to some specific climate impacts on health as well as the development of monitoring programs and community adaptation strategies.

We would like to thank the residents of the communities taking part in these studies to date, without whom this work would not have been possible. The participating and support of the Regional Inuit Organizations and Community organizations in Labrador, Nunavik and the Inuvialuit Settlement Region is greatly appreciated. We gratefully acknowledge the financial support provided for various aspects of this work by the Canadian Institutes for Health Research, Climate Change Action Fund, the Northern Ecosystem Initiative, Health Canada and the MSSS-Québec.

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Increased Fall Storminess, Threats to Public Infrastructure, and the Effects on Fall Whaling in Barrow, Alaska

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There has been a recent increase in the frequency of fall storms in the Barrow, Alaska, area. It is particularly striking when one examines the period from 1970 to the present, roughly the period during which the North Slope Borough (NSB) has been in existence.

The fall storminess has led to coastal erosion and damage to public infrastructure, including coastal roads. The Barrow Utilidor and the Barrow landfill and wastewater lagoon are threatened by every major storm. Currently, the only option is to build gravel berms along the coast and keep rebuilding and replenishing them throughout a storm. This involves round-the clock operation of all available equipment, and often means that equipment operates in the surf. If this berm rebuilding process were to fail, the consequences for Barrow could be catastrophic.

NSB heavy equipment has been used in moving fall whales to butchering sites and the skeletons to a disposal site on Point Barrow. This year, there were several fall storms prior to whaling. There was concern about the condition of the heavy equipment, which led to concern about using and possibly damaging equipment during whaling, leaving the whole community vulnerable to storms.

The Barrow Whaling Captains Association (BWCA) decided to open the fall whaling season extremely late. This choice was to increase the chances of taking small rather than large whales and also to allow the sea to cool in hope of safer boating conditions. The BWCA suggested that small whales be taken, and even suggested a restriction be placed on the size of whales that NSB equipment would handle.

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Late Holocene Environmental Change in SW Greenland and the Fate of the Norse

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Icelandic Sagas report that settlers from Iceland founded a Norse colony in South Greenland around AD 985. When the Norse arrived in Greenland they quickly established themselves as farmers in the deep and lush fjords of southwest Greenland and in a colony 500 km farther to the north. The Norse colonists brought with them the social and religious culture and structure of Western Europe, and only slowly adapted a few surviving strategies from the Inuit way of living.

The Norse arrived in Greenland close to the peak of the Medieval warming period. This climatic condition made it possible for the Norse to sustain a farming culture, where livestock was grazed in mountain pastures during the summer season while grass was harvested at the lower altitude around the farms for winter fodder. The Norse, however, lived their European way of life under harsh and marginal sub-arctic conditions and thus at the edge of sustainability and almost 500 years after their arrival they had vanished from Greenland by the end of the 14th century.

The northern Norse settlement was depopulated around AD 1350 according to Icelandic annals, whereas the Norse community in south Greenland survived another hundred years. The last historical document about the Norse in Greenland is an Icelandic account of a wedding taking place AD 1408. What subsequently happened to this northernmost outpost of western Christianity has not been recorded by any written sources.

The Medieval Warm Period in which the Norse arrived in Greenland was followed by a climatic deterioration in south Greenland around AD 1400 that culminated in the Little Ice Age. The impact, on the Norse, of these natural climate changes has been considerable. Medieval Icelandic documents report on expanding sea ice off southeast Greenland just after the Norse colonization that hampered the important shipping trade with Iceland and Europe. The climatic deterioration resulted in a disastrous shortening of the summer season and an intensification of the wind stress over southern Greenland, which enhanced soil erosion. Also, a relatively fast subsidence (3 m/1,000 years) of this part of Greenland led to flooding of the lowlands that were important for the Norse farming culture. Climatic and hydrographic changes in the Norse settlement area were therefore significant during the period when the Norse vanished from Greenland and may have contributed to the loss of the Norse culture.

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Arctic Climate Research and Traditional Ecological Knowledge: The Quantitative Aspect of TEK

Raphaela Stimmelmayr Tanana Chiefs Conference

The world is changing rapidly. Observations and climate modeling indicate that Alaska's climate and ecosystems are at the forefront of the predicted global climate change. Direct and indirect effects on traditional foods, on local weather, snow, and permafrost and ice conditions, characterize climate change currently experienced on a village level.

Many uncertainties remain in predicting climate scenarios and impacts, in particular, on local and regional scales. A still largely untouched source of information relevant to Alaska's ecosystem health and potential pollution-climate change interactions is local and Traditional Ecological Knowledge (TEK) held by Alaska Natives. The poster will describe and discuss methodological aspects of TEK, in particular; provide examples on the quantitative nature of TEK; and thoughts on how TEK measurement units can be integrated into arctic climate models.

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Adjustment to Reality—Cases of Detached, Dependent, and Sustained Community Development in Greenland

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Student Poster

Greenland has experienced three major socio-economic shifts during the 20th century, all of them induced by the interactions between the natural system of climate change, and the socio-economic and socio-technical system of resource exploitation.

The first was the shift from a sea mammal-based economy to fisheries during the 1910s through 1920s, and this was due to a marked increase in sea temperature, resulting in a decrease in the sea mammal stock, combined with a dwindling world market for blubber and sealskin. The cod became the dominating species, but the fisheries were characterized by a diverse use of locally available resources. The second was the shift from cod fisheries to a mono economy based on shrimp fisheries during the 1980s, due to a reduction in sea temperature, eliminating the spawning possibilities of the cod stock and giving way to a massive expansion of the shrimp fisheries, especially facilitated by a shift from inshore to offshore fisheries. Third is the ongoing shift toward a more diversified focus of fisheries, with shrimp as the backbone of the economy, but with Greenland halibut offering substantial contributions in the northern regions.

Even though the pattern of changes in resource base has been more or less similar all over Greenland, the socio-economic changes have been remarkably varied, and the poster illustrates three characteristic patterns. Sisimiut, presently the second-largest settlement in Greenland, has been characterized by its ability to adjust positively to the changes, showing initiative, innovativeness, and adequate social capital. The community shows all signs of a self-sustaining dynamic.

Paamiut, on the other hand, was able to adjust to the first transformation process to fisheries, and was chosen by the authorities as a model for the modernized industrial processing of renewable resources. With the changes in resources the highly centralized decision structures were not able to adjust to the changes, eventually leading to a decay of society as well as economy. The case illustrates a typical example of a dependent development dynamics.

Tasiilaq, and East Greenland in general, shows a third approach to respond to changes. Several attempts have been made by the authorities to involve the community in the development process, but generally without any enduring success, partly due to some differences in resource characteristics between the east and west coasts of Greenland, and partly due to the long duration of semi-colonial relationships to both Denmark and West Greenland. This case illustrates the characteristics of a detached development dynamics.

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HUMAN/ENVIRONMENT INTERACTIONS: POSTERS

Modeling Impacts of Hydrologic and Climatic Change on Humans in the Arctic

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Freshwater is critical to the sustainability of humans and their activities in the Arctic. The availability and status of water resources may promote good health or propagate disease, support the distribution and quality of plants and animals used for subsistence, and promote or impede access and development. Water has always been and will always be integral to the culture of humans in the Arctic. In the past thirty years, the climate in the Arctic has warmed appreciably and there is evidence for a significant polar amplification of global warming in the future. Recent studies suggest that climate change will have a significant impact on arctic hydrology. Changes in the hydrologic cycle will affect both the presence of surface water and the thermal balance in soil. While preliminary evidence suggests a changing climate will have a significant impact on the hydrologic cycle in arctic regions, very little evidence is available to predict how the quality and quantity of freshwater available to humans is likely to change. Coupled with regional-scale environmental dynamics are local-scale human behaviors and resulting activities in response to perceived change, available technologies, and existing policy infrastructures.

The overall objective of this research is to understand how humans interact with freshwater on local scales in selected parts of the Arctic, how these interactions have changed in the recent past, and how they are likely to change in the future. We seek to develop a model that will allow better prediction of climate-induced changes in the hydrologic cycle, particularly at local scales. This will be accomplished by incorporating an understanding of both the sociocognitive and biophysical drivers and feedbacks mediated by human systems. This study will take place on the Seward Peninsula where clear climate-induced changes in the hydrologic cycle are already being observed. We will utilize community collaboration, historical documentation, field observations, laboratory experimentation, and agent-driven Boolean modeling to achieve the project goals. This project will work closely with another OPP project "Social-Ecological Resilience and the Future of Remote Resource-Dependent Communities" to cross-link data, optimize methodology sharing, and test theory.

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The Common Raven *(Corvus corax)* on the North Slope of Alaska: Wildlife Management and the Human Dimension

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Student Poster

As we begin to identify the linkages and feedbacks among social and ecological systems within the context of global change, the need for collaborative and integrated research among natural scientists and social scientists becomes increasingly more apparent. Avian conservation efforts are directly shaped and influenced by social processes. Interdisciplinary research in this area can bring unique and comprehensive approaches to designing and implementing effective conservation strategies. Here, I propose an interdisciplinary research framework to address the relationships between the ecology of the Common Raven *(Corvus corax)*, impact of the raven on tundra nesting birds, oil development on the North Slope of Alaska, and local knowledge of ravens. This research will provide a model for integrating ecological and social information for proposed raven management.

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Shaking up the Neighborhood: Historic Perspective on Resilience and Vulnerability in the Gulf of Alaska

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Student Poster

Around the North Pacific Rim of southern Alaska, human mobility and subsistence strategies have been heavily influenced by punctuated events such as earthquakes, tsunamis, and volcanic ash fall, and by more-or-less gradual fluctuations in climate and sea level. Recent geological and geophysical research projects have identified such phenomena, which impacted prehistoric human occupation throughout the Kodiak Archipelago. In spite of the intermittent recurrence of these dramatic and unpredictable events, human populations and dominant cultural strategies in this region have persisted, and even flourished. This is in part because of regional diversity that provided opportunities for settlement relocation and maintenance of traditional resources. It may also relate to the early development of social coping mechanisms, as some scholars have proposed.

Evidence from the Tanginak Anchorage on Sitkalidak Island is used to suggest 7,500 years of continuous habitation, despite indications that occupants experienced major changes in the physical character of the landscape and probable disruptions in resource acquisition. We explore evidence for occupation and abandonment at the Tanginak Spring Site and other sites along this ecologically productive stretch of coastline, and assess the various human responses that catastrophic events and landscape change may have elicited.

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Human Impacts to Fire Regime in Interior Alaska

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Student Poster

A thorough analysis of human impacts on interior Alaska's fire regime demonstrates that human activities have a large effect on fire regime. The Fairbanks region, which has a large human population with road influences, differs from two other regions with low human populations and no roads.

Alaska's land is separated into four classes designated for different levels of protection: critical, full, modified and limited, listed from high- to low-level protection. In the Fairbanks region, humans have impacted fire regime by causing more fires in certain fuel types and doubling the length of the fire season. Despite the increased number of fires in the Fairbanks region, more of the Fairbanks region is designated to receive a high level of suppression. Therefore, less area of land burns in the Fairbanks region, even with fuel type controlled for.

For Alaska as a whole, human ignitions and suppression have only a minor effect on fire regime, and climate strongly influences the total area burned. However, in areas where people live, human ignitions account for most of the area burned, and climate has no significant effect on area burned. In the Fairbanks region, the reduction in area burned, due to fire suppression, will, over the long term, increase the proportion of flammable vegetation on the landscape and therefore increase future fire risk to people. In summary, the net effect of people on Alaskan fire regime has been to reduce area burned, reduce its sensitivity to climate variation, and increase the future risk of fires that threaten human life and property.

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The Archeology of Glaciers and Snow Patches: A New Research Frontier

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Approximately 10% of the earth's land surface is covered by ice. Global warming is rapidly melting ice and exposing rare archeological remains. These sites are important to understanding the role of high latitude and high altitude environments in human adaptation and cultural development. GIS modeling is being used to identify areas exhibiting high potential for the preservation and discovery of frozen archeological remains. Areas holding the highest potential for archeological site discovery are: 1) ice-covered passes used as transportation corridors, and 2) glaciers and areas of persistent snow cover used by animals that attracted human predators. The primary goals of this research are to first predict site potential throughout Alaska's Wrangell St. Elias National Park and Preserve, and then to make the model applicable to other glaciated regions of Beringia and other high-altitude and high-latitude environments.

In 2001 and 2003 numerous archaeological and/or paleontological sites were discovered on melting glaciers and perennial snow patches. Historic artifacts included horse hoof rinds and horseshoe nails, cans, tools, historic debris, and even the remains of an entire building. Historic artifacts are most commonly discovered below the equilibrium line altitudes (ELA's) of large valley glaciers at an elevation of approximately 3,400 feet (~1036 m) that were used as trails and passes over mountain ranges. Prehistoric artifacts include antler projectile points, wooden arrow and atlatl shafts, a birchbark container, and an atlatl foreshaft with a hafted stone projectile point. Prehistoric finds are most commonly associated with relatively small, perennially frozen snow patches and cirque glaciers where people hunted caribou and sheep. Numerous paleontological specimens including mammalian hair and fecal material, the remains of sheep, caribou, carnivores, and other medium-sized mammals, rodents, birds, and fish have been discovered.

Glaciers and perennial ice patches most probably used by humans in the past can be detected using GIS modeling using three types of data layers, or coverages: 1) social/cultural, 2) biological, and 3) physical. The areas of highest archeological potential were presumed to be those geographic locales where the three data sets overlapped spatially. Influential layers included biologic and geologic factors such as mineral licks, lithic sources, transportation corridors, and large-mammal species ranges (caribou, sheep, goats, moose and bears). The social/cultural coverages were compiled from historic, ethnographic, and archival sources as well as through interviews with knowledgeable individuals. In addition to historically documented trails, proximity and accessibility to known archeological and historic sites are important variables. Large-mammal species distribution data were developed through analysis of the biological literature, studies conducted by the Alaska Department of Fish and Game and the National Park Service, and informant interviews. The physical data layers are derived from the geologic literature, low-level color aerial photography, satellite imagery, USGS maps, and open file reports, and in consultation with knowledgeable researchers and resource managers. When used in conjunction with data on elevation, aspect, and slope, the statistical analysis of hyperspectral imagery and thermal bands are important variables for predicting potential site locales on relatively small perennial snow and ice patches. These data layers, along with factor proximity weighting using exponential decay with distance from ice and multiple regression analyses, are used to further analyze and predict potential site locales. Field survey is then used to test and refine the site potential model.

Global warming presents an unprecedented opportunity to identify glaciers, ice fields, and similar environments that hold high potential for the exposure and discovery of frozen archeological remains. This is an exciting new archeological frontier from which rare, unique, and important artifacts made from organic materials are being discovered across the globe. These discoveries hold great potential to revolutionize anthropological theories ranging from high-altitude and high-latitude adaptations to human colonization. Global warming has created an urgent need to develop scientific methods to locate and preserve frozen organic remains because these depositional environments are ephemeral and exposed organic materials soon decompose or are destroyed.

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Analyzing the Implications of Climate Change Risks for Human Communities in the Arctic: A Vulnerability Based Approach

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Student Poster

In the Arctic, climate change and its effects are expected to be felt early and most keenly. Important changes in key climatic parameters are already evident and climate models indicate that greater changes are forthcoming. As a consequence, climatic risks including geophysical hazards, alteration in marine and terrestrial ecosystems, and increased unpredictability of environmental conditions, are expected to increase in frequency, intensity, and geographic distribution.

It is not, however, the impacts of climate change per se that are problematic for human communities. Communities can cope with climatic risks to a certain extent. The key issue is that of vulnerability. Vulnerability concerns the susceptibility for harm in a system relative to a stimulus, and recognizes that the implications of climate change for communities depend not only on the impacts of climate change but also the ability to cope. In doing so, it helps us understand those circumstances that put people and places at risk, and conditions that reduce the ability of people and places to respond. This paper outlines how a vulnerability-based approach can be used to analyze the implications of climate change for human communities.

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Multi-Decadal Response of a Seabird to the Arctic Oscillation

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Unlike the abundant evidence of biota responding to lower-latitude atmospheric oscillations, the Arctic Oscillation's (AO) effect on biological populations is sparse, primarily due to the paucity of long-term studies in the region. A population of Black Guillemots, an arctic seabird resident in the Arctic for the entire year, was monitored near Point Barrow from 1975–2002 and found to show phenological and demographic sensitivity to the winter AO. While major changes were associated with the 1989 shift from a cold- to a warm-phase AO, the population also demonstrated sensitivity to interannual AO variation throughout the study. A positive winter AO was associated with an earlier spring snowmelt that facilitated access to nesting cavities and allowed earlier egg laying. The majority of annual variation in timing of egg laying was explained by the previous winter AO, occurring twelve months earlier, revealing a previously unreported lag in local cryospheric response. The positive winter AO in the 1990s was also correlated with an almost 50% decline in the breeding population, apparently due to the accelerated melting of pack ice, the preferred guillemot foraging habitat in all seasons.

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A Critical Review of the "Regime Shift/Junk Food" Hypothesis for the Steller Sea Lion Decline

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It has been hypothesized that periodic changes in the climate of the North Pacific caused the decline of the Steller sea lion population observed in the 1980s, by causing large increases in consumption of gadid (e.g., pollock) fishes with low nutritional value, and decreases in consumption of osmerid and clupeid fishes (e.g., capelin and herring) with high nutritional value. According to this regime shift-junk food hypothesis, changes in food habits of Steller sea lions stemmed from climate-induced restructuring of fish communities associated with a regime shift in 1976–77. The consequences for sea lions, associated with greater and lesser consumption of gadids and forage fish, respectively, are thought to have included decreased reproductive success or survival due to nutritional stress.

We examine this hypothesis through a critical re-analysis of fishery and survey data, gadid and clupeid recruitment and biomass time series, Steller sea lion and other otariid food-habits information in the North Pacific Ocean and throughout the world, and information related to the nutritional worth of gadids and other prey species, including proximate analyses of prey composition as it varies seasonally and spatially. We conclude that 1) recruitment to pollock populations was unrelated to or decreased following the 1976–77 regime shift; 2) herring populations increased in the 1980s following the regime shift; 3) it is unlikely that herring and other forage fish have ever dominated the fish community in terms of total biomass; 4) gadids have consistently been prominent parts of otariid diets in the North Pacific and other parts of the world; 5) food-habits data do not support the conclusion that sea lion diet composition changed radically after the regime shift; 6) the energetic value of any particular prey item depends on the season in which it is eaten and the costs of obtaining it (at times gadids have higher energetic density than osmerids or clupeids); and 7) a diet with too high a proportion of osmerids or clupeids is known to be detrimental to many species of marine mammals and fish. While changes in the environment of Steller sea lions have certainly occurred over the past thirty years and could have contributed to the creation of sub-optimal conditions, we conclude that it is unlikely that they, or the high proportion of gadids in the diet, are the primary causes of the recent and ongoing decline in the western Steller sea lion population.

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Potential Arctic Terrestrial Ecosystem Feedbacks to Climate Change: A Consideration of Component Carbon Pool Dynamics

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Arctic and boreal forest ecosystems are important in the context of global climate change because their soils contain extensive organic carbon (C) reserves, and because they are expected to undergo the most rapid increases in temperature. Most experimental and C modeling research in these ecosystems has been focused on summertime biogeochemical processes. Here, we report on an experimental manipulation study aimed at characterizing the controls on the annual patterns of gross CO_2 production in two common Swedish sub-arctic ecosystems. Our results indicate that the removal of plants and their current year's litter significantly reduced the sensitivity of gross respiration to intra-annual variations in soil temperature for both heath and birch understory ecosystems. We conclude that respiration from soil organic matter C stores in these ecosystems is less temperature responsive than respiration derived from recent plant C fixation. Furthermore, the amount of substrate being respired was significantly higher in the birch understory. Finally, our results suggest that respiration derived from accumulated bulk soil organic matter constitutes about half of total ecosystem CO_2 production during winter. Accurate assessment of the potential for positive feedbacks from high-latitude ecosystems to CO_2-induced climate change will require the development of physiological models of net ecosystem C exchange that account for such differences in temperature sensitivity between C pools, and substrate respiratory coefficients between vegetation types, and that integrate over summer and winter seasons.

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Increasing Sea Ice in Baffin Bay and Adjacent Waters Threatens Top Marine Predators

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Global climate change is expected to have severe impacts on arctic ecosystems, yet predictions of ecosystem effects are complicated by region-specific patterns and non-uniform trends. Twenty-four open water overwintering areas (or "microhabitats") were identified for eight indicator seabird and marine mammal species in the eastern Canadian high Arctic and West Greenland. Localized trends in the available fraction of open water were examined in each region, based on approximate sea ice concentrations within the ice pack from microwave SSMR/SSMI passive brightness temperatures gridded at a 25 km^2 resolution between March 1978–2001. Decreasing trends in the fraction of open water in focal areas were identified in northern and central Baffin Bay and coastal West Greenland, following well with regional cooling and increased sea ice in the West Greenland ecosystem. Trends in localized habitats were unclear in Hudson Bay and Foxe Basin regions. The species-specific biological importance of each microhabitat was elucidated based on occurrence, distribution, and abundance of seabirds and marine mammals, and potential population and life history consequences of sea ice trends were identified. Decreasing open water is predicted to differentially impact foraging efficiency, oxygen, and prey availability of those predators that rely on these areas during the winter. Of the indicator species, the narwhal (*Monodon monoceros*) is among the most vulnerable due to high winter site fidelity in Baffin Bay, where the entire population (>50,000 individuals) occupies dense pack ice for six months of the year with less than 3% open water. Decreasing trends in the area of open water were found on the two primary narwhal wintering grounds (25,000 km^2), significantly so in northern Baffin Bay (-0.04% per year, SE 0.02). In combination with this trend, inter-annual variability in the fraction of open water was observed to be significantly increasing at +0.03%

per year (SE 0.006). The limited number of leads and cracks available to narwhals during the winter period, in combination with decreasing trends in open water and increasing trends in annual variability, leaves little doubt that their high site fidelity makes them exceedingly vulnerable to changes in arctic sea ice conditions.

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Ringed Seals and Changing Snow Cover on Arctic Sea Ice

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Ringed seals *(Phoca hispida)*, the most abundant seal species in the Northern Hemisphere, depend on subnivean lairs for protection from cold and predators. Newborn ringed seal pups weigh about 4 kg and are especially vulnerable to predation and cold exposure. They are protected from both threats by occupying lairs from birth in April through the first 6–8 weeks of their lives. Past anomalous weather events that caused the lairs to collapse or melt before ringed seal pups were weaned led to unusually high predation rates by polar bears, arctic foxes, gulls, and ravens. We recorded air temperatures between -5 and +5° C in occupied lairs, while temperatures (including windchill effect) outside those lairs ranged from -7 to -61° C. Those ambient temperatures were often well below the lower critical temperature (-25° C) for the pups, while the temperatures in lairs were consistently well above that limit. We used radiotelemetry to monitor the emergence of ringed seals from subnivean lairs in spring 1999, 2000, 2001, 2002, and 2003. At the same time, we monitored weather conditions and snow temperatures at 5 cm-depth increments. Abandonment of lairs was associated with the snowpack turning isothermal, at which time its thermal and structural integrity was compromised. The snow cover failed especially early in 2002, and by mid-May of that year, all of the seals had abandoned lairs, exposing pups prematurely to the threat of predation. Increasingly early snowmelts associated with climate change are likely to negatively impact ringed seal populations through increased juvenile mortality.

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Modeling Modes of Variability in Carbon Exchange Between High-Latitude Terrestrial Ecosystems and the Atmosphere: A Synthesis of Progress and Identification of Challenges

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Terrestrial ecosystems of high latitudes are responsible for storing a substantial proportion of global soil organic carbon. The release of carbon from soils of high-latitude terrestrial ecosystems to the atmosphere has the potential to influence concentrations of carbon dioxide and methane in the atmosphere. Substantial progress has been made in representing the role of soil thermal dynamics in the seasonal exchange of carbon dioxide between high-latitude ecosystems and the atmosphere. Model analyses of responses of carbon dioxide exchange to inter-annual variability in temperature exchange suggest that responses of carbon dioxide exchange depend substantially on changes in the length of the growing season and changes in soil moisture. Inter-annual responses of methane also depend substantially on responses of soil moisture, particularly changes in the water table. At decadal time scales, simulated responses of carbon dioxide and methane to warming depend substantially on the representation of carbon and nitrogen transformation in the soil and how the response of the nitrogen cycle influences the uptake of carbon by vegetation. Additional progress in predicting responses of carbon dioxide and methane of high-latitude terrestrial ecosystems to future climate variability and change requires 1) better representation of spatial variability in soil moisture and water table depths, and 2) improved understanding of carbon and nitrogen transformation in soils.

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Linkages Between Climate, Growth, Competition at Sea, and Production of Sockeye Salmon Populations in Bristol Bay, Alaska, 1955-2000

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Bristol Bay, Alaska, supports one of the largest and most valuable salmon fisheries in the world. Salmon abundance in Bristol Bay and other northern areas more than doubled after the 1976–77 marine climate shift. However, in 1997–98, a major El Niño event led to unusual oceanographic conditions and Bristol Bay sockeye salmon production was unexpectedly low. Nevertheless, the effect of climate on biological mechanisms leading to greater salmon survival and production are poorly understood. In order to test several hypotheses linking climate to salmon growth, interspecific and intraspecific competition, and salmon production, we measured annual marine and freshwater scale growth of Bristol Bay sockeye salmon, 1955 to 2000.

We discovered that the significant increase in sockeye salmon abundance during the late 1970s was associated with significantly greater salmon growth during the first and second years at sea, whereas growth during the third year was below average. Thus, the 1976–77 marine climate shift led to greater prey production, resulting in greater early marine growth and survival of sockeye salmon. Contrary to previous reports of density-dependent growth during early marine life, we found density-dependent growth was not readily apparent until the last year at sea when reduced growth typically has less effect on survival. In contrast with the 1976–77 climate shift, the 1997-98 El Niño led to significantly smaller size of adult sockeye salmon and lower survival, further supporting the hypothesis that growth at sea is strongly associated with climate and salmon survival.

Analysis of sockeye salmon scales also led to the discovery of significant interspecific competition between Asian pink salmon and Bristol Bay sockeye salmon in the North Pacific Ocean. The competition effect, whose detection was facilitated by the unique two-year cycle of pink salmon, led to reduced growth of sockeye salmon and a 35% reduction in survival at sea. Competition with pink salmon resulted in a loss of at least 59 million Bristol Bay sockeye salmon ($310 million ex-vessel value) during 1997–2000. This finding of competition provides the first clear evidence that interspecific competition at sea can lead to reduced growth and survival of salmon. Competition at sea has important new implications for stocks protected under the Endangered Species Act and for salmon hatcheries, which release more than four billion juvenile salmon into the North Pacific Ocean each year.

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Climate, Snow, and Hydrology in Tundra Ecosystems: Patterns, Processes, Feedbacks and Scaling Issues

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Tundra has acted as a long-term carbon sink, sequestering atmospheric carbon in soils that today contain ca. 11% of total world soil carbon. Few ecosystem-level studies have been conducted in the Arctic, and carbon exchange of tundra vegetation types is generally poorly represented in global ecosystem models. The landscape comprises mosaics of vegetation "units" (graminoid, dwarf-shrub, or lichen dominated) at scales of tens to hundreds of meters, in relation to topography, soils, and hydrology (wet, mesic, dry).

Tundra exhibits hierarchically scaled spatial heterogeneity, with plant community mosaics at landscape scales and variation in the predominant mosaic elements at regional to pan-arctic scales. This heterogeneity reflects hierarchically scaled spatial and temporal environmental heterogeneity that has not yet been adequately captured by efforts to model the impacts of climate change upon arctic tundra. This requires spatially and temporally explicit process-based modeling at the landscape scale. Such models must be underpinned by ecosystem studies that will provide the data necessary to achieve adequate representation of landscape processes and of their spatial and temporal variability.

Through a series of measurements at complementary spatial and temporal scales, coupled with suitably robust upscaling and modeling approaches, we will provide an improved spatially and temporally explicit representation of trace-gas and energy flux across the tundra landscape. The project builds upon existing work carried out in programes in the American Arctic and the European Arctic. The scientific advances over previous work are three-fold: 1) a clarification of spatial scaling issues in trace-gas and energy exchange in tundra ecosystems; 2) an improved understanding of the seasonal controls over trace gas and energy exchange, particularly the poorly studied winter and early spring period; and 3) the provision of a northern European perspective on spatial and temporal scaling issues in tundra ecosystems.

Fieldwork is being carried out on sub-arctic tundra ca. 7 km from the Swedish Royal Academy of Science Abisko Scientific Research Station (ANS), Sweden (68°21'N, 18°49'E). We are partitioning "field-scale" measurements of net fluxes across the landscape, made by an eddy flux tower, into components relating to the elements of the tundra mosaic by means of series of plot-scale measurements of trace gas fluxes. These measurements sample the fine-scale mosaic across the landscape and through time, in terms of hydrology and soil processes. We are also attempting to predict trace gas fluxes both spatially across the landscape and temporally through the seasons in terms of contributions from identified soil-vegetation-hydrology associations within particular parts of the landscape mosaic.

Plot-scale measurements within specific components of the landscape mosaic, outside the footprint of the eddy flux tower, include a series of manipulations of winter/late spring snow cover. Snow fences are being used to increase snow depth and duration, and early melt of snow to alter growing season length of the tundra vegetation. Impacts of manipulations upon vegetation phenology and physiological development throughout the growing season are being monitored, along with impacts upon C turnover and partitioning (assessed by integrating canopy photosynthesis and ecosystem respiration measurements made using a "whole ecosystem" cuvette). Soil organic matter mineralization rates and major nutrient (N and P) fluxes are also being assessed, both during the thaw period and throughout the winter season; we regard measurements of winter soil processes, and development of novel techniques in this area, as of particular importance to the project. We are utilizing in situ measurements plus controlled laboratory experiments to improve mechanistic understanding of the key processes and the factors affecting rates and fluxes.

Spatial upscaling from the plot-scale to the scale of the eddy correlation tower footprint will be achieved by mapping the plant community mosaic and micro-topography within the footprint. Field-scale fluxes will be modeled as distance- and area-weighted functions of plot-scale fluxes measured for the principal elements of the mosaic. This will provide quantitative estimates of the relative contributions of each element to the overall flux measured at the field scale. In addition, it will enable upscaling of the results of the snow-lie manipulations to provide quantitative estimates of field-scale impacts. The same approach will also be used to upscale from our measurements to estimates of landscape-scale fluxes by mapping the relative extent of each element of the hydro-topographical mosaic. The UK Meterological Office Surface Exchange Scheme (MOSES) is being utilized for surface flux simulations for each landscape element. These will be similarly upscaled to provide landscape- to regional-scale flux estimates, and the importance of explicit partitioning of the fluxes from the landscape elements assessed.

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Plant and Soil Responses to Neighbor Removal and Fertilization in Acidic Tussock Tundra

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Studies in tundra at Toolik Lake suggest that the characteristics of the dominant plant species may affect the rates of biogeochemical cycling of carbon and nitrogen. For example, the shrub *Betula nana* becomes dominant in fertilized tussock tundra, leading to greater above-ground storage of carbon in woody biomass than in fertilized non-acidic tundra, where *Betula* is rare. As climate changes, nutrient availability is expected to increase, and species composition is expected to shift.

To what extent do species characteristics affect ecosystem capacity to respond to perturbation, and the trajectory of response? If plant species coexist in tundra by partitioning soil nitrogen, can they use soil resources freed up by shifts in species composition? In an experimental manipulation, we removed single species and groups of species, in the presence and absence of fertilization, starting in 1997. After two years of treatment, vascular plants mostly responded positively to fertilization, but did not show many significant responses to neighbor removal. However, removal greatly increased soil nutrient availability, particularly in treatments that removed the most plant biomass. Whether plants will be able to take advantage of increased nutrient availability over the longer term, or whether these nutrients will be lost from this ecosystem, remains to be seen.

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Effects of Canopy Representation on Carbon Balance Simulations at Treeline

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Modeling vegetation systems has become one of the most powerful methods available for predicting the response of modern vegetation assemblages to future changes in climate. There is a wealth of data indicating how major vegetation types have changed their distribution in response to Holocene vegetation changes. One major vegetation feature that has changed location through the Holocene is the forest-tundra boundary found in both arctic and alpine locations. As the treeline is approached, the forest canopy thins and the physiognomy of the trees changes from an arboreal growth form to a mat-like growth form called "krummholz." Full-sized upright trees, dwarfed trees and krummholz are often found within a short distance of each other. The primary difference between the tree types at treeline locations is the canopy structure. Krummholz trees tend to have their foliage concentrated at the top of the canopy, whereas dwarf-trees have more foliage near the bottom of the canopy. The canopy structure influences the distribution of light within the tree canopies and also has an effect on the temperatures within the canopy.

This study reports on the measurement and modeling of the effects of these gradients within treeline canopies. During the summers of 2000 and 2001 vertical gradients in light and temperature were measured within krummholz and dwarf tree canopies of *Abies lasiocarpa* and *Pinus contorta* at the forest-tundra boundary (treeline) in northwestern Montana. The magnitudes of the gradients differ between the canopy forms.

The location of the forest-tundra boundary should be controlled in part by carbon balance. Trees at locations beyond the boundary should not be able to maintain positive carbon balances. Therefore, by predicting carbon balance across the landscape a potential treeline can be predicted. The location of this treeline will be influenced by canopy structure if the magnitudes of the gradients in light and temperature within the different canopy types are great enough. Simulations of carbon balance using a physiologically mechanistic model (ATE-BGC) for different canopy types indicate that there are differences in predicted treeline position using the two canopy types. Gradients in light are the most important. Temperature gradients can be important, but have much less effect on location and spatial pattern of the treeline ecotone.

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The Effects of Soil Moisture on Carbon Processes in Upland and Lowland Tundra Ecosystems

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Global climate change, in the form of increasing temperatures, melting permafrost, longer growing seasons, and altered precipitation and hydrologic drainage patterns is leading to dramatic changes in the Arctic, while the full implications of such changes on regional terrestrial carbon cycle dynamics is unknown. We use a terrestrial ecosystem process model and eddy covariance flux network measurements to investigate spatial patterns and temporal variability in vegetation net primary production (NPP), soil heterotrophic respiration and net CO_2 exchange of lowland and upland tundra communities on the Alaskan North Slope. In particular, we investigate the sensitivity of these processes to ground water depth and soil moisture and the potential effects of altered drainage and precipitation on the regional carbon cycle under a changing climate.

Our results indicate that the regional carbon budget is highly sensitive to variations in ground water depth. Drying soils yield marked increases in soil heterotrophic respiration, increased N cycling, and a decrease in soil C storage even though increased N cycling and associated soil nutrient availability under drier soil conditions yields higher NPP and increased C sequestration by vegetation. In lowland tundra, however, we find evidence that decreases in ground water depth and soil moisture can lead to moisture stress, decreasing both vegetation productivity and soil microbial activity. Our results indicate that the capacity of the tundra as a net source or sink for atmospheric CO_2 under current and projected future warming will depend largely on precipitation and soil hydrological impacts to soil respiration. Warming with increased or no net change in soil moisture will likely lead to increased NPP, relatively stable soil carbon pools, and net C sequestration, while regional warming and drying will likely lead to increased soil respiration and net C losses.

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Paleo Investigations of Climate and Ecosystem Archives (PICEA): Holocene Fire and Vegetation History from Ruppert Lake, Brooks Range, Alaska

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Student Poster

A major unresolved issue in predicting arctic ecosystem responses to future climatic change is the extent to which shifts in boreal forest will be driven solely by climate or by feedbacks among climate, vegetation, and fire. The PICEA project utilizes paleoecological records from north-central Alaska and a model of boreal ecosystems to document patterns and identify causes of past ecosystem change.

An initial goal of the project is to understand how fire regimes changed in relation to vegetation and existing interpretations of Holocene climate. A ca. 10,000-year-old sediment core from Ruppert Lake provides a continuous record of macroscopic charcoal accumulation with an average temporal resolution of twenty-five years, and fossil pollen provides a broad-scale record of Holocene vegetation change. Charcoal accumulation rates suggest that fire was a component of the ecosystem when *Betula* shrub tundra dominated ca. 10,000 calibrated years before present (yr B.P.). Similar evidence of fire exists as small populations of *P. glauca* first invaded *Betula* shrub tundra ca. 9,000 yr B.P. and with the addition of *Alnus,* ca. 7,600 yr B.P. Increases in both charcoal accumulation and the frequency of distinct charcoal peaks ca. 5,000 yr B.P. suggest an increase in the size, frequency, and/or severity of fires. This change coincides with a regional addition of *P. mariana* and a shift from *P. glauca*- to *P. mariana*-dominated forest communities. Forest composition changed little throughout the late Holocene, but charcoal accumulation at Ruppert Lake decreased again ca. 2,500 yr B.P. Independent climate proxies for this period suggest a shift to cooler temperatures.

Our results support the concept that fire regimes in boreal forests are broadly controlled by climate. However, links between forest change and changes in fire regimes suggest that vegetation can play an important intermediary role between climate and fire.

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Climate And Land-Surface Systems Interaction Centre (CLASSIC)

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The IPCC and others [1, 2] identify as a priority the need to reduce uncertainty in assessing actual and potential effects of climate change. If this is to be achieved, our understanding of the feedbacks that exist between the land surface and the atmosphere must be greatly enhanced beyond the current state of the art. In particular, current Land-Surface Parameterizations and Dynamic Vegetation Models must be improved, within both Global and Regional Climate Models, to fully reproduce these interactions. These models should be able to exploit dynamic, spatially comprehensive data on the terrestrial biosphere, such as those provided from Earth Observation (EO). A new NERC Centre of Excellence, CLASSIC, has been established this year (2003) to address the scientific challenges that this raises. CLASSIC consists of a core consortium of four institutions, combining expertise in EO science, satellite-sensor technology, and environmental (hydrological, ecological, and climatological) modelling and analysis, namely: 1) the University of Durham; 2) the University of Wales Swansea; 3) the Hadley Centre for Climate Change Prediction and Research; and 4) the NERC Centre for Ecology and Hydrology. The scientific objectives of the Centre will be delivered via a coordinated programme of fundamental research, a scientific exchange scheme, and a series of education and training initiatives. CLASSIC will act as a focal point for land-surface observation and modelling within the UK and internationally. It aims to be outward looking and inclusive—exchanging data, methods, software, and knowledge through active collaboration with other institutions in the UK and overseas — and to build upon existing international links, participating in activities such as EOS, ISLSCP, GOFC, GCP, GEWEX, IGBP, PILPS, CEOS, and collaborative land-surface calibration and validation activities.

Climate-Land Surface Feedbacks

Feedbacks between the land surface and the atmosphere are key determinants of climate at a range of spatial (local–global) and temporal (seasonal–centennial) scales. Since the pioneering work of Charney et al., who demonstrated the potential role of vegetation removal in maintaining drought in sub-Saharan Africa [3], numerous studies have shown a sensitivity of climate to both natural and human-induced changes in land-surface properties [4–10]. Similarly, many of the properties involved — e.g., vegetation type and cover, soil moisture, and snow cover — evolve continuously in response to atmospheric/climatic forcing, while the initial forcing may be amplified or dampened as a consequence of their interaction [11–13]. Cox et al. [14], for example, suggest that die-back of the Amazonian rainforests over the next 50–100 years, caused by "greenhouse" warming, may accelerate global climate change. Similarly, Zeng et al. [15, 16] demonstrate the role of vegetation dynamics in enhancing regional climate variability at inter-annual and inter-decadal time scales, while presenting evidence to suggest that soil moisture stress on vegetation may contribute to the persistence of regional droughts. An enhanced understanding of these feedback mechanisms would greatly improve the "skill" of climate model predictions and, hence, assessment of the actual and potential effects of climate change.

An assessment of variations in land-surface properties and processes that are affected by climate oscillators, such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), is also of paramount importance. Since these oscillators have a degree of predictability, studying their interactions with land-surface processes and investigating the feedback mechanisms involved would improve our ability to assess their likely impact, perhaps months in advance. Recent studies also suggest that climate oscillators operating on different time scales interfere with one another, enhancing or negating each other's effect [17]. Understanding these interferences and interactions will assist in the development of improved land-management strategies to cope with their adverse impacts and, where possible, to make maximum use of their beneficial effects.

Representation of Land Surface/Climate Feedbacks in GCMs

In the 1980s, greatly improved land-surface parameterizations (LSPs) were developed in which the transfer of mass, heat and momentum between the land surface and the atmosphere was linked with variations in biophysical properties in an integrated framework [18, 19]. Thus, for example, changes in leaf area index (LAI) not only alter interception and transpiration, as had previously been the case, but also albedo and surface roughness, altering both the surface energy balance and momentum transfer. LSPs are regulated by a set of inter-dependent biophysical properties, the values of which were initially based on land-cover classifications derived from conventional atlases [20] and existing ecological data sets. Because of their static nature, however, these data do not account for the full spatial and temporal variability of the biosphere, so that important within-class spatial heterogeneity, as well as interannual and longer-term (decadal to centennial) variations, cannot readily be modelled.

One way to obtain dynamic biophysical properties for LSPs is to use Dynamic Vegetation Models (DVMs) [21, 22]. These calculate key biophysical properties as a function of climate, soils, and competition between species. DVMs are an attractive alternative to the use of prescribed biophysical properties because they can interact fully with a GCM and, hence, provide a means to explore potential feedbacks between vegetation and climate. They enable plant growth and competition to be simulated interactively and the related land-surface properties to be updated accordingly [23–25]. As a result, they can simulate the terrestrial (land) carbon budget and the broad distribution of biomes across the globe. Even so, considerable uncertainties remain, notably in terms of plant and soil respiration, and soil water storage [26]. Enhancements are also required to the representation of the surface radiation balance, sub-grid-scale spatial heterogeneity, and seasonal/regional vegetation patterns.

The Role of Earth Observation and Considerations of Sub-Grid Scale Effects

The representation of biophysical properties in current LSPs can be further improved through the use of satellite sensors [27–29]. These produce spatially comprehensive (m–km) and temporally explicit (daily–interannual) information on the biosphere — e.g., vegetation type, cover/amount and phenology, with ongoing research into the retrieval of properties such as surface roughness, land-surface temperature and soil water content—that can be incorporated into LSPs through model initialization, forcing, and validation, or by means of data assimilation [30]. Sellers et al. [25] have, for example, adapted their Simple Biosphere (SiB) model to take advantage of satellite-sensor data by incorporating the photosynthesis formulations of Farqhuar, Berry, and Collatz. The revised model, SiB2, uses fAPAR (fraction Absorbed Photosynthetically Active Radiation) as the key parameter to calculate photosynthesis: fAPAR is also linked with LAI, surface roughness length and albedo. Estimates of fAPAR are obtained from satellite sensors such as NOAA/AVHRR [17, 25, 31].

The use of EO data in this context has been made possible by continuing increases in the computational power available to climate modelling. This has allowed the specification of finer spatial grids, in both GCMs and RCMs, that are more appropriate to an analysis of land-surface processes under changing environmental and climatic conditions. As a result, there is an increasing awareness of the sensitivity of spatially averaged meteorological parameters to sub-grid-scale land-surface variability and of the need to incorporate such variability, within climate models to improve seasonal to inter-annual forecasting [32]. Indeed, a new generation of LSP has recently been developed that accounts for mixtures of vegetation types within a single grid box and that allows these components to interact with the overlying atmosphere [33]. Although relatively crude at present, these models provide the framework for a more explicit description of sub-grid scale variability and feedback.

Importantly, advances in climate modelling have been matched by developments in both the science and technology of Earth Observation (EO). Specifically, the latest generation of satellite sensors produces data that are better calibrated, are more accurately geo-referenced, have finer spectral and spatial resolution and, hence, are more appropriate to the needs of the climate modelling community. At the same time, improvements in our understanding of, and ability to model, the physics of radiation transport at Earth's surface mean that we are now better able to convert remotely sensed measurements of surface-leaving radiation into accurate estimates of the key land-surface properties, or to assimilate EO data directly into LSPs. Moreover, the archive of EO data is now sufficiently long to detect and represent inter-annual cycles and trends in the global biosphere [34].

Despite this, the full potential of EO data has yet to be realized. Most LSPs still obtain a substantial part of their input from land-cover classifications, while satellite data are seldom used in studies with DVMs. Thus, it is only recently that climate-related, inter-annual variations in vegetation—readily detected in satellite-sensor data—have been investigated using LSPs. Similarly, few LSPs can exploit, directly, information on episodic and seasonal changes in vegetation contained in EO data. Implementing these features in LSPs/DVMs would greatly increase their realism and would provide an additional means by which to validate the results produced by such models.

Scientific Objectives

The objectives of CLASSIC are i) to examine how EO data can be used to improve LSPs and DVMs in GCMs/RCMs, ii) to increase our understanding of land surface/climate feedbacks, and iii) through enhancements to climate model predictions, to improve our assessment of the actual and potential effects of climate change. More specifically, CLASSIC will address a number of scientific challenges identified as priorities by the IPCC and others [1, 2], including the need to:

1. Improve the representation of sub-grid scale land-surface processes in current LSPs/DVMs, based on EO data, to enhance the "skill" of GCM/RCM predictions of future climate change;
2. Improve the understanding and representation of the feedback mechanisms that enhance or suppress the effects of climatic oscillators on land-surface properties and processes, as detected in EO data;
3. Achieve tighter coupling of EO data with explicit hydrological and ecological sub-models within LSPs and DVMs;
4. Understand the causes of, and hence attempt to resolve, inconsistencies between modelled and observed climates, particularly in terms of the shortcomings of current climate model simulations of observed inter-annual and sub-decadal patterns of change over land; and
5. Understand and predict the regional consequences of global climate and environmental change, including climate variability.

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Feeding on the Bottom at the Top of the World

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The trophic structure of the benthic community of the deep Canadian Basin in the Arctic was investigated. We used stable isotope analysis to elucidate how closely linked deep-sea benthos is to the pelagic and ice-associated production. $d^{15}N$ ratios are indicative of relative trophic relationships with a stepwise enrichment between trophic levels (TL) of about 4‰. Mean $d^{15}N$ isotopic values for water column POM was 5.1‰. Benthic animals ranged from 10.2‰ to 17.7‰ in their $d^{15}N$ isotopic values with most of the organisms falling into the second and third TL with respect to the POM values. This suggests that little fresh phytodetritus is reaching the seafloor.

The benthic community consists mainly of deposit feeders consuming refractory material, e.g., many polychaetes; and of scavengers, predators, or omnivores. In contrast to the benthic system, distinctive herbivores (TL1) and first order predators (TL2) were present at the sea ice and the upper water column, with $d^{15}N$ values between 5–7‰ and 10–13‰, respectively. Few pelagic/ice organisms fell within the third TL suggesting that the link between the pelagic/sea ice and the benthic system is through sinking of grazers and their products (e.g., fecal pellets, molts, dead animals) to the seafloor rather than through direct input of algal material to the benthos.

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Non-invasive, Highly Resolved Observations of Sea Ice Biomass Dynamics: A Link Between Biogeochemistry and Climate

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Climatic changes in high latitudes sensitively affect the persistence and dynamic of sea ice. Covering around 12 million sq km, sea ice constitutes an ecologically important, transient interface between the atmosphere and the polar ocean. The buildup of autotrophic biomass inside sea ice commences early in the season in response to the availability of light and nutrients, at a time when productivity in the water is typically low. Its release constitutes a concentrated pulse of energy to winter starved organisms and increases the vertical organic carbon flux. Sea ice primary productivity estimates range between 30% and 50% of the arctic marine primary production. Biomass estimates are, however, based on invasive, scattered ice-core observations of low vertical resolution in particular across the ice-water interface.

A thin pronounced layer of algae at the sea ice-water interface spatially occurs where fluctuations of sea-ice mass, energy transfer, and phase transitions are greatest. Due to the extremely transient nature of the ice-water interface, highly temporally resolved data are needed to assess the significance of event-driven export processes from the ice. The vulnerability of sea ice biomass to temperature anomalies is amplified by meltwater runoff and exposure to the water column. Pelagic populations of grazers respond sensitively to the timing, availability, and distribution of food, such as algae micro-layers at the bottom of the ice. Current field methods lack the resolution to understand the causal relations of short-term sea ice export events and resulting population fluctuations. Sediment traps allow integrated information over time and water volumes, but do not reflect ambient food concentrations at the ice-water interface and hence lack the sensitivity to resolve event-driven deviations from annual means, which matter in the survival of species.

We describe the seasonal in situ evolution of autotrophic biomass along highly spatially resolved vertical profiles in and across the ice-water interface, by means of a new in situ fluorescence system inside fast-ice of the Chukchi Sea during a seven month deployment. Algae growth commenced very early (January) with distinct colonization patterns leading to a biomass peak at the end of April and export to the water.

Our in situ system illustrates the advantages of a non-intrusive approach in describing the response of biomass to climatic disturbances at the ice-water interface. These achievements lay the foundation of an autonomous biological sea ice buoy information system which integrates with existing arctic climatic and physical sea ice recording systems, allowing a investigation of feedback mechanisms between arctic climate, marine food webs, and biogeochemical fluxes directly below sea ice.

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Using Gray Whales to Track Climate Change in the Alaskan Arctic

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Climate warming has resulted in extreme seasonal retreats and thinning of sea ice in the western Arctic. However, other less obvious effects of warming on arctic marine communities are difficult to discern. Because marine mammals are apex predators in the short food chains common to the Arctic, they can be good indicators of ecosystem response to climate change.

Gray whales, due to their benthic foraging capability, may provide a clear link between atmospheric forcing and the pelagic-benthic coupling processes required to support a dense prey base. To explore this link, a five-day aerial survey was conducted over the Chirikov Basin in the northern Bering Sea during summer 2002. In the 1980s, the Chirikov Basin was a prime gray whale feeding area, with an extremely productive benthic prey community. However, no comprehensive assessments of whale or prey distribution and abundance have occurred since then. The 2002 survey for gray whales revealed restricted distribution in the basin and a three- to seventeen-fold decline in sighting rates compared to the 1980s. Many more whales were seen north of Bering Strait, where the sighting rate was 0.49 whales/km compared with only 0.03 whales/km in the basin. Available measurements of biomass suggest a downturn in prey abundance that began as early as 1983, when estimates of gray whale population size were still increasing.

These data, and reports of hundreds of gray whales feeding in the south-central and northwest Chukchi Sea and southeast of Kodiak Island in the Gulf of Alaska, suggest that benthic communities in the Chirikov Basin may no longer support large aggregations of whales and that gray whales are foraging elsewhere. Since multi-decade, time series data are available for the Chirikov Basin, long-term studies of this area are encouraged to investigate predator-prey responses to changing ocean climate.

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Commander Islands as the Significant Point for Monitoring Some Dangerous Changes in Beringia Ecosystem

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The number of sea otters has dramatically declined during the past seven years in some parts of the Northern Pacific. At this time, we can foresee a catastrophical reduction in the population of sea otters near the Aleutian Islands. They seem to disappear for unknown reasons. Almost the same situation is occurring with Steller sea lions and some other species that are in the top level of the feeding chain. All these facts clearly display that something is drastically wrong with the natural functions in the whole ecosystem of the Bering Sea.

Around the Commander Islands we found biologically productive and diverse marine environments. The main reason for this is the unique combination of geological and hydrological factors around this small area. Also, near the Commander Islands there are huge, active underwater volcanoes. Altogether, these factors form favorable conditions for phyto- and zooplankton which form the base of living for other high range organisms in the ecosystem. Another factor is the biodiversity of seaweed near the coastal line of the islands. It is one of the richest areas for seaweed, by species and biomass, in the world.

So, for natural, historical, economic, and other reasons the unique ecosystem of the North Pacific's Commander Islands is an essential focal point for field expedition work and for conservation projects.

The urgency of the initiatives to be funded has been confirmed many times over by UNESCO. In 1993 the Commander Islands received the status of "Nature Reserve" under Russian Federal Law. In 2002 they received "Biosphere" Status under UNESCO guidelines. We are hopeful (with all documents ready and with UNESCO approval) that in 2003 the Commander Islands will obtain the highest status of "World Nature Heritage Site" under UNESCO.

The Commander Islands can serve as an important model and preserve for study of the Bering Sea ecosystem's natural processes, which are now starting to suffer stagnation and collapse. Financial support is needed for a practical course of action in the Commander Islands.

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A High-Resolution GIS-based Inventory of the West Siberian Peat Carbon Pool

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The West Siberian Lowland (WSL) contains the world's most extensive peatlands and a substantial fraction of the global terrestrial carbon pool. Despite its recognition as a carbon reservoir of great significance, the extent, thickness, and carbon content of WSL peatlands have not been analyzed in detail. This paper compiles a wide array of data into a geographic information system (GIS) to create a high-resolution, spatially explicit digital inventory of all WSL peatlands. Detailed physical characteristics for nearly 10,000 individual peatlands (patches) are based on compilation of previously unpublished Russian field and ancillary map data, satellite imagery, previously published depth measurements, and our own field depth and core measurements taken throughout the region during field campaigns in 1998, 1999, and 2000. At the patch level, carbon storage is estimated as the product of peatland area, depth and carbon content. Estimates of peatland area are validated from RESURS-01 satellite images, and peatland depth and carbon content are validated by laboratory analysis of core samples. Through GIS-based spatial analysis of the peat areal extent, depth, and carbon-content data, we conservatively estimate the total area of WSL peatlands at 592,440 km^2, total peat mass at 147.82 Pg, and the total carbon pool at 70.21 Pg C. The uncertainty of this carbon pool is estimated to be -30.03 to 34.48 Pg C, with greatest uncertainty found in thin northern peatlands. Our analysis concludes that WSL peatlands are more extensive and represent a substantially larger carbon pool than previously thought: previous studies report 9,440,273,440 km^2 less peatland area and 15.1130.19 Pg less carbon than found in this analysis.

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Seasonal and Non-linear Effects of Experimental Climate Change on High Arctic Ecosystem Carbon Exchange

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The cold, dry landscapes of the high Arctic are characterized by polar desert, polar semi-desert, and fen ecosystems. In this extreme environment, plant cover increases from less than 30% up to 100% in association with the increased availability of water. The variation in net ecosystem carbon exchange across these ecosystems, and their response to climate change, will depend on the coupling of carbon and water in biological processes, photosynthesis, and respiration, and will be related to plant cover. Clearly, the availability of water and input of energy are critical to the dynamics of high arctic-landscapes. Our research is aimed at understanding the mechanisms controlling carbon exchange through the experimental increase of energy and precipitation inputs to these ecosystems.

This year was the first of a five-year climate manipulation study in a polar semi-desert ecosystem that includes two components: 1) multiple levels of climate warming through increased infrared radiation and 2) a factorial study of warming and increased summer rainfall through weekly additions of water. Our initial results indicate that early in the growing season only an increase in both rainfall and energy led to greater carbon storage. Net carbon flux peaked in mid-July just prior to a natural mid-summer rain event. Following this rain event, ecosystem respiration rates increased and led to decreased carbon fluxes. Water additions no longer affected respiration rates, but did increase gross photosynthetic production in warmed plots. A 2° C warming of the tundra decreased net carbon fluxes, but a 4° C warming did not double this carbon loss. At peak biomass, carbon storage was greatest in fen ecosystems, where warming with open-top chambers increased net carbon fluxes through a decrease in respiration rates. Vegetation cover and species composition affected ecosystem carbon exchange with the prostrate willow species having a pronounced affect. Based on these results, changes in species composition and inter-annual variation in climate (the timing of large summer rain events) may have the most dramatic effects on ecosystem carbon exchange in response to our climate manipulations.

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The Impact of Snow-up Timing on Arctic Winter Soil Temperatures

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For ecosystems that are snow-covered during a significant part of the year, variations in the nature and timing of snowpack development can produce large year-to-year differences in the thermal regime of the soil. Here we use continuous snow-ground interface temperature measurements from two consecutive winters taken across a variety of vegetation types on the Seward Peninsula, Alaska, to quantify these differences.

The first winter (2000–01) had an above-average snowpack that was largely in place by November. The second winter had a below-average snowpack that did not develop until January. Interface temperatures the second winter averaged 10° to 20° C lower than the first despite similar air temperature regimes. Moreover, distinct differences in soil thermal regime that developed as a function of different vegetation types the first winter were largely absent in the second. The measurements also show that with increasing canopy height and stem diameter, the thermal regime of the soil is spatially more heterogeneous. The results show that larger changes in winter soil thermal regime can be induced through changes in the timing of the development of the winter snowpack than can be induced through step changes in winter air temperature.

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The Effect of Temperature, Water Content, and Light Intensity and Quality on Nitrogen Fixation in High Arctic Tundra Vegetation

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Student Poster

Terrestrial primary production in the high Arctic is often limited by low nitrogen content of the soil. Due to general low precipitation in these regions, deposition of nitrogen is not sufficient, and thus, biological nitrogen fixation is a major contributor of the nitrogen-input and thus plays an important role for terrestrial arctic ecosystems. Free-living, moss-associated (epiphytic) and symbiotic (lichen) cyanobacteria are considered to be the main source of biologically fixed nitrogen in polar regions. As with other microbial processes, cyanobacterial nitrogen fixation is also strongly influenced by abiotic factors. In the case of cyanobacteria these factors may be soil water content, soil temperature, and the quality and quantity of solar radiation. Models of future climate predict significant changes in climate conditions in the Arctic, which in turn may affect the cyanobacterial nitrogen-fixation activity.

To understand how possible climate changes might affect nitrogen fixation and primary production in terrestrial arctic ecosystems we measured the long-term effect of enhanced UVB radiation, and the effect of changes in the water, temperature, and light regime on the nitrogen-fixation activity in arctic vegetation on Svalbard, high Arctic. Moss-associated cyanobacteria exposed to experimentally enhanced UVB radiation (representing a 15% ozone depletion) for six years showed a more than 40% reduction of their nitrogen fixation activity compared to controls. Moreover, temperature, soil water content, and light intensity also had a strong and clear effect on the nitrogen fixation activity. However, our results showed that only severe changes in soil temperature and light intensity will have a significant effect on the nitrogen fixation activity in high-arctic soils, whereas even slight changes of the water content may clearly affect this process.

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PHYSICAL FEEDBACKS: PRESENTATIONS

Atmospheric Heat Transport as a Feedback on the Arctic Climate

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Positive feedbacks unique to the cryosphere are thought to render the Arctic particularly sensitive to anthropogenic climate forcing. But the arctic climate is also subject to tremendous heat influx from lower latitudes via the atmosphere and ocean. In this study we assess the impact of changes in the atmospheric heat transport on the arctic climate, subject to increased greenhouse gas forcing, in several global climate models. We find that by the time carbon dioxide levels double, the heat transport increases by several watts per square meter in nearly every model we examined. The increase is especially great in spring and summer, when it can most easily enhance ice-albedo feedback. The increase is due primarily to an increase in latent heat transport resulting from the increase in the moisture content of the atmosphere at lower latitudes. Transport by sensible heat decreases, owing to a decrease in the meridional temperature gradient, but in most models, it is not enough to compensate for the increase in latent heat transport.

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The Role of Surface Albedo Feedback in Climate

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A coarse-resolution coupled ocean-atmosphere simulation where surface albedo feedback is artificially suppressed by prescribing surface albedo is compared with one where snow and sea ice anomalies are allowed to affect surface albedo, as the model was originally designed. Canonical CO_2-doubling experiments were performed with both models to assess the impact of surface albedo feedback on equilibrium climate response to external forcing. Both models were also run for 1,000 years without external forcing to assess the impact of surface albedo feedback on internal variability and compare it with the feedback's impact on the response to CO_2 doubling.

Sea ice albedo feedback behaves differently in the internal variability and CO_2-doubling contexts. In contrast, snow albedo feedback in the Northern Hemisphere behaves very similarly; a given temperature anomaly in snow-covered regions produces approximately the same change in snow depth and surface albedo whether it was externally forced or internally generated. This suggests the presence of internal variability in the observed climate record is not a barrier to extracting information about snow albedo feedback's contribution to equilibrium climate sensitivity. This is demonstrated in principle in a "scenario run", where estimates of past, present, and future changes in greenhouse gases and sulfate aerosols are imposed on the model with surface albedo feedback. This simulation contains a mix of internal variations and externally forced anomalies similar to the observed record. The snow albedo feedback to the scenario run's climate anomalies agrees very well with the snow albedo feedback in the CO_2-doubling context. Moreover, the portion of the scenario run corresponding to the present-day satellite record is long enough to represent the model's snow albedo feedback in the CO_2-doubling context. This suggests the present-day satellite record could be used to estimate snow albedo feedback's contribution to equilibrium climate sensitivity.

The Ice/Ocean Interface During Summer: Implications for Ice-Albedo Feedback

Miles G. McPhee McPhee Research Company

An important, perhaps dominant, component of the ice-albedo feedback is absorption of solar energy by the upper ocean when sun angles are relatively high. The basic concept is simple: as solar radiation penetrates open water (or thin ice) with relatively low albedo, temperature of the mixed layer rises. Ocean-to-ice heat flux increases, enhancing ice melt at the base and exposed edges, creating more low albedo area, increasing energy absorption, and so on. Under certain conditions the effect can be quite dramatic; however, two factors tend to ameliorate the strength of the feedback.

Storage and sequestration of heat in the upper ocean. Melting at the ice/ocean interface occurs by the transfer of heat and salt through thin sublayers adjacent to the interface where molecular effects dominate. Since the molecular diffusivity of salt is smaller than thermal diffusivity (by a factor of about 200), salt controls the rate of melting. In early summer, this allows a more or less steady increase in mixed layer temperature, meaning that a significant fraction of the solar energy entering the upper ocean heats seawater instead of melting ice. Later in the season, much of this stored heat is absorbed by melting ice, but at a time when sun angles are considerably lower, decreasing the albedo feedback effect. From several observational studies, heat and salt transfer processes are relatively well understood and generally incorporated in most numerical models of ice-ocean interaction. Less well understood is the sequestration of heat in the lower part of the early summer mixed layer. This occurs in mid-summer when relatively rapid "flushing" of fresh water from the surface creates a seasonal pycnocline that protects the water below from surface mixing. During the AIDJEX (1975–76) year in the Beaufort Gyre, this trapped summer heat never was recovered, meaning that over the annual cycle, the net ocean heat flux was downward.

Under-ice melt ponds and false bottoms. In summer, fresh meltwater running off at floe edges and percolating through porous, relatively warm ice, collects in concavities under thin ice. Thin layers of fresh ice, called false bottoms, form at the interface between these "under-ice melt ponds" (at 0° C) and the underlying seawater (typically -1.6° C). This reverses the usual temperature gradient at the interface, so that even though seawater is above freezing, the heat flux under false bottoms is often downward. Simple modeling shows that a relatively small areal coverage of false bottoms can significantly decrease the aggregate bulk ocean-to-ice heat transfer. The obvious importance for albedo feedback is that not only do the false bottoms decrease overall transfer of heat from the ocean, but also preferentially protect thin ice from basal melting.

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The Ice-Albedo Feedback in a Changing Climate: Albedos from Today and Reflections on Tomorrow

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The ice-albedo feedback mechanism plays a key role in the heat budget of sea ice and snow in the Arctic. It is a positive feedback that is of great import to climate studies. There has been significant recent progress in defining the key elements of the ice-albedo feedback, in quantifying the feedback, and incorporating improved treatments of the feedback into general circulation models. Recent research has found that the ice-albedo feedback is largely determined by the timing of seasonal transitions, the duration of summer melt, and the evolution of melt ponds. It is typically assumed that a warming climate would mean a longer melt season, with an earlier onset of summer melt and a later freeze-up, more ponded sea ice, and a stronger feedback. These changes could be incorporated into the existing theoretical framework in a straightforward way. It is possible, however, that the changes will be revolutionary, rather than evolutionary. There may be a fundamental change in the nature of the sea ice cover that will cause a profound change in the ice-albedo feedback. There are obvious impacts from a warming climate, such as larger amounts of open water resulting in a decrease in albedo and greater heat input to the system. There are also more subtle consequences, such as those due to enhanced amounts of first-year ice or changes in winter snow accumulation. The impact of more first-year ice on the ice-albedo feedback may depend on the degree of deformation. Deformed first year ice may have morphological properties, and an albedo evolution, similar to multiyear ice. In contrast, undeformed first year ice will have extensive pond coverage, no surface scattering layer, lower albedos, and an accelerated ice-albedo feedback. Deeper snow on the sea ice would reduce surface melt early in summer, but would likely result in greater pond coverage and potentially greater surface ablation. A shallow snowpack would retard the formation of melt ponds, resulting in a larger albedo. Changes in the ice-albedo feedback could also impact interactions between the terrestrial and marine environment with serious consequences. For example, early melting of the terrestrial snowpack would result in significant increases in the total heat input. In coastal regimes, this would hasten the melting of the shorefast sea ice, extending the ice-free period and exposing the coast to more storms and erosion.

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A Data-Model Comparison Study of the Arctic Ocean's Response to Annular Atmospheric Modes

Bruno Tremblay Columbia University[1], **Robert Newton** Columbia University[2], **Peter Schlosser** Columbia University[3]

A simple model simulating the basin-scale barotropic response of the Arctic Ocean to changes in the North Atlantic Oscillation (or Arctic Oscillation) is presented. The model distills concepts developed by Hunkins, Proshutinsky and others into an analytic calculation of the balance between inputs of vorticity to the surface of the Arctic Ocean and their dissipation within the ocean-ice system. The results of the model are compared with tide-gauge data from various coastal stations and with a new synthesis of isotope tracer data collected during the past fifteen years. The observations and theory are applied to the problem of freshwater storage in and export from the Arctic Ocean. Using this simple model and preliminary 3-D coupled ice-ocean model simulations (validated against tracer and sea-surface height observations) we discuss potential links between atmospheric variability, Arctic Ocean dynamics, and the export of freshwater to the Nordic Seas.

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The Influence of Cloud Feedbacks on Arctic Climate Change

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By greatly affecting radiative fluxes at the surface and the top of the atmosphere, clouds exert a strong influence on modern climate and can be expected to play an important role in shaping future climates. To investigate the impact of clouds under greenhouse forcing, a global climate model is run with and without cloud feedbacks in a 2 x CO_2 scenario. The prognostic cloud changes in the standard simulation enhance greenhouse warming at all latitudes, accounting for one-third of the global warming signal. This positive feedback is most pronounced in the Arctic, where approximately 40% of the warming is due to cloud changes. The strong cloud feedback in the Arctic is caused not only by local processes but also by cloud changes in lower latitudes, where positive top-of-the-atmosphere cloud radiative forcing (CRF) anomalies are larger. The extra radiative energy gained in lower latitudes is transported dynamically to the Arctic via moist static energy flux convergence. The results presented here demonstrate the importance of remote impacts from low- and middle-latitudes for arctic climate change.

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Using a Spatially Distributed Model to Characterize the Influence of Permafrost on Hydrological Processes

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Student Poster

In the sub-arctic environment, the presence or absence of permafrost is a strong factor in controlling both soil moisture dynamics and hydrology. Soil moisture, which displays a high spatial and temporal variability, is an important variable in understanding and predicting a large number of processes including land-atmosphere interactions, permafrost aggradation/degradation, and fire frequency and severity. In order to understand and predict ecosystem response to a changing climate and resulting feedbacks, it is critical to quantify the interaction of soil moisture and meteorology as a function of climatic processes, landscape type, and vegetation.

The primary goal of our research is to describe, simulate, and predict soil moisture dynamics and all other hydrologic processes everywhere throughout a sub-arctic watershed. The model we are developing will be used as a tool to better understand the effects of vegetation and soil type, presence or absence of permafrost, the amount and timing of precipitation, and disturbance (such as wildfire) on soil moisture dynamics. Three small sub-basins of the Caribou-Poker Creeks Research Watershed (CPCRW), located 48 km north of Fairbanks, Alaska (65º10’N, 147º30’W), are the areas selected for study. These small sub-basins, which are underlain with approximately 3%, 19%, and 53% permafrost, are simulated using the TopoFlow hydrologic model to explore differences in permafrost versus non-permafrost areas.

The TopoFlow model is a process-based, spatially distributed numeric model developed to simulate soil moisture dynamics and other hydrologic processes. This model can be used to simulate spatially distributed processes, such as soil moisture dynamics or snowmelt, as well as point measurements such as stream flow within the model domain. Simulation results reflect many of the distinguishing characteristics of the sub-arctic environment, including the representation of discontinuous permafrost, distributed vegetation types, and a groundwater flow.

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Covariability in Arctic Climate Variables: Observations and Model Simulations

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Student Poster

The complex interactions among climate variables in the Arctic have important implications for potential climate change, both globally and locally. Modeling has many advantages for studying these interactions. In addition to the traditional approach of validating individual variables with observed fields, we demonstrate that a comparison of covariances among interrelated parameters from observations and GCM output provides a tool to evaluate the realism of modeled relationships among variables. We analyze and compare a combination of conventional observations, satellite retrievals, and GCM simulations to examine some of these relationships.

The results at daily and monthly scales are shown in this paper as well as the temporal and spatial pattern of the relationships. It shows that the highest correlations between daily changes in pairs of variables for all three data sets occur between surface temperature and downward longwave flux, particularly in winter. There is less variability in GCM output; in part, because there is greater spatial averaging. Although the satellite products can be used to examine some of these relationships, additional work may be needed to ensure consistency between changes in radiative components of the energy budget and other retrieved quantities. The GCM's relationships between variables agree well with in situ observations, which provides some confidence that the GCM's representation of present-day climate is reasonable in high northern latitudes.

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Fram: A New Basin Scale Model of Sea Ice Dynamics

Max Coon NorthWest Research Associates

Sea ice is a central element in the Earth's climate system. In order to understand past climatic variability and to improve our predictive capabilities, modeling efforts must include a realistic representation of sea ice. Here we will describe a multi-year effort funded by Mineral Management Services (MMS) and NASA to implement, test, and validate a new sea ice dynamics model. The model will treat the ice cover as an anisotropic elastic/plastic strain-hardening material in the permanent ice pack, and will include the correct frazil/pancake behavior in the marginal ice zone. The two striking facts about present ice dynamics models are that they: 1) do not reproduce the oriented fracture patterns of openings and closings in the pack, and 2) do not accurately model the effects of frazil/pancake ice formation in the marginal zone. These two areas produce a) the most ice growth, b) the most turbulent heat flux to the atmosphere, c) the most salt flux to the ocean, and d) the most energy dissipation due to slippage, ridging, and rafting. Existing sea ice models have shown limited success for predicting the degree to which any given lead will open for prescribed, or even observed, forcing conditions. These shortcomings will be addressed in the new model.

The development of a new sea ice dynamics model is facilitated by two significant developments that will allow for the accurate prediction of lead orientation and the magnitude of lead opening. First, large-scale motion data for specified material points on the arctic ice cover, derived from satellite data, are now available. Second, theoretical and numerical procedures have been recently developed for describing crack formation through the use of decohesive crack models. The important aspect of such models is that the existence, as well as the orientation *and* the opening or closing of cracks, are predicted through the use of the same variables for which measurements on the arctic sea ice have been obtained. A proposed data assimilation procedure (to keep the model on track as far as lead orientations and ice concentrations) would help constrain the simulation results for operational model application. This proposed program will set the stage for significant advancement in the modeling and understanding of the Arctic and Southern Ocean sea ice covers.

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Evaluation of the True Ice Mass in the Arctic Ocean

Nikolay Doronin “EcoShelf” Company

The sea ice is an important component of the heat- and freshwater balance of the Arctic Ocean. Mean export of the ice through the Fram Strait is estimated at 2,900 km^3/year. Its inter-annual variability reaches 700 km^3. These values have been obtained by monitoring the ice draft with the help of moored upward-looking sonars.

It is important to note that volume parameters do not exactly characterize the true ice mass, which is a component of the heat- and freshwater balance. A considerable part of the ocean area is covered with ridged ice. In the process of ridging, ice floe fragments are frozen together with empty spaces in between. The real share of emptiness can be determined by drilling of the ridges.

In practical application the task of evaluation of the true ice mass was aimed at determination of ice load on offshore oil platforms. For that purpose, in the Barents Sea region and in the region of the Sakhalin shelf during the past ten years, a series of expeditions have been carried out. Direct observations of the morphology of ice formations have been fulfilled. With the help of airborne stereo photography the area covered with ridged ice, ridge height and width have been determined. Directly on the ice these measurements were validated by contact methods. Expeditions deployed on the ice measured the draft of pressure ridges, width of the keel, and angles of sail and keel.

To determine consolidation of the ice in the pressure ridge a special electric thermal drill has been designed. Presence of empty spaces has been recorded by drilling speed.

These field measurements suggested it was possibile to develop an empirical model of the pressure ridge and to evaluate the correlation between its volume and true ice mass. It was found that ice consolidation in the pressure ridge had remarkable inter-annual variability and strongly depended on regional conditions, ice dynamics, freezing speed, and other factors. However, in both the Barents Sea region and the Sakhalin Shelf, accounting for empty spaces in ridges gave considerable correction in evaluation of the total ice mass. For ridges 5–8 m thick up to 30% of the volume was empty. Therefore we can conclude that geometrical characteristics obtained by remote sensing give an overestimated volume of sea ice.

It is important to note that described measurements have been carried out in the regions covered with the first-year ice. For climatic tasks it is necessary to determine consolidation in the pressure ridges on multi-year ice, which covers most parts of the Arctic Basin.

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The Role of Sea Ice Mechanics and Deformation in Arctic Climate Change

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Spatial and temporal variations in sea ice deformation are largely controlled by ice mechanics. In turn, ice mechanics and associated formation of leads and ridges control the thickness distribution and, hence, the ice mass balance, the heat flux between the ocean and the atmosphere, and the oceanic salt flux.

As a consequence, ice mechanics provides an important physical feedback between the ice thickness distribution and environmental change. This poster will discuss a variety of feedbacks, ranging from inertial and tidal variability in sea ice deformation to the role of ice dynamics in climate warming. In addition, it will show evidence from the field and from the laboratory of scale-independent failure processes which are important to high-resolution atmosphere-ice-ocean modeling.

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Variability in Simulated Arctic Freshwater Budgets

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The arctic freshwater cycle is important for global climate because of its possible influence on deep water formation in the sub-arctic seas. A characterization of the climatological state and variability in arctic freshwater budgets is a necessary first step for examining the global implications of the arctic hydrological cycle. Coupled general circulation models are useful tools for investigating these processes because they provide complete self-consistent data sets of the relevant fields.

In this study, the mean state and variability of the components of the arctic freshwater budget from a 1,000-year integration of the Community Climate System Model, version 2, are presented. From a comparison to the available observations, it appears that the model has a reasonable simulation of the arctic hydrological cycle. We discuss possible mechanisms that drive variations in the budget terms. In particular, the influence of large-scale modes of variability, such as the Arctic Oscillation, are investigated. Results from a climate-change integration with increasing atmospheric CO_2 levels are also shown and illustrate possible future changes in the arctic hydrological system. Preliminary results on possible feedbacks of the arctic freshwater cycle on the global thermohaline circulation are also discussed.

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An Eddy-admitting Global Ice-ocean Simulation

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Physical oceanographers have determined that the downwelling limbs of the thermohaline circulation occur in relatively few places in the global ocean, notably in the Greenland, Labrador, and Mediterranean Seas and a few locations around the Antarctic continent. Except for the Mediterranean, all of these locations are at least seasonally affected by the presence of sea ice.

Recent modeling work at Los Alamos National Laboratory has focused on factors affecting the global thermohaline circulation. Here we present an eddy admitting simulation of the global ocean circulation using an ice-ocean coupled model. The simulation features a vigorous thermohaline circulation with global mass and heat transports that agree well with observational estimates, and it provides a consistent picture of the freshwater fluxes through the Arctic Ocean and its marginal seas. Net downwelling occurs near the sea ice edge in selected areas.

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Field Studies on Basin-Scale Water Balance on North Slope, Alaska

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Student Poster

Hydrology acts as acritical link among land, ocean, and atmosphere. Therefore, to better understand the changing environment, with a specific focus on global warming, hydrological processes may serve as the greatest purveyors of such knowledge. Using the boundaries of a given watershed, the hydrologic cycle can be represented in measurable components (generally they are runoff, precipitation, evapotranspiration (ET), and subsurface and surface storage) by the water balance equation. This is the core of understanding a regional environment because its changes are reflected in the inputs/outputs at a watershed boundary. Moreover, research has reported that the Arctic is the most susceptible to a changing climate. Combined, the above interests have given fuel to study watersheds specific to the arctic and sub-arctic regions.

On the North Slope of Alaska, water balance studies have been conducted on selected sub-watersheds of the Kuparuk River basin, from as early as 1985. For the headwater basins, limited surface and subsurface storage of water can be assumed with little error and therefore the inputs (snowmelt and rainfall) and outputs (runoff and evapotranspiration) are accounted for with relatively less error compared with watersheds with either/both surface and subsurface storage. Further interpretation reveals snow and ice have a significant influence on the water balance. For the studied watersheds in the Kuparuk region, more than half of the runoff is generated from snowmelt. During extreme years, over 90% was due to snowmelt. Because these events yield half the yearly discharge volume, snowmelt is expectedly the peak runoff event. Recent rain events in the Kuparuk River basin have shown summer storms to produce the peak flow on record.

In addition to studying snow and ice effects on the water balance, evapotranspiration usually accounts for most of the water loss during the summer months. However, ET activity may vary over the Kuparuk basin, depending on moisture availability and local conditions. Although studying such regions in the Kuparuk basin continues to provide insight into the hydrologic activity of an arctic watershed, this only allows a regional understanding. To study environmental change in the polar regions, it is necessary to conduct intercomparisons of research watersheds across the pan-arctic. Subsequently, a compilation of water balance data has been initiated from additional research watersheds from around the circumpolar region. This effort will aid in integrating arctic basins on a larger scale and their hydrologic responses to a changing climate.

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The Physical and Hydrological Impacts of a Wildfire on an Arctic Tundra Ecosystem, Seward Peninsula, Alaska

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Student Poster

Alaska is a fire-dominated ecosystem differing from the northern forests of the continental U.S. and Canada in many important aspects. The fire-prone areas of Alaska are primarily in the interior boreal forest region. The discontinuous nature of the permafrost distribution tends to promote a mosaic of vegetation types with dense forests of fire-prone black spruce and thick organic layers developing in permafrost areas that have not burned in recent history. Fires also occur, on a lower frequency, in the treeless tundra regions of the Seward Peninsula and Yukon Kuskokwim Delta. Although the cause is unknown, fire records demonstrate a marked positive trend in the numbers of fires over the past fifty years in the tundra regions of the Seward Peninsula.

Arctic and boreal ecosystems are an important part of the Earth system as they occupy 22% of the land surface. Global circulation models (GCM) indicate that global change will be most noticeable in the Northern Hemisphere. Increased air temperatures are likely to influence vegetation type and the distribution of permafrost. Changes in arctic ecosystems may have consequences for regional and global climate. Global change will probably cause an increase in wildfire return frequency. Wildfires may have drastic impacts on short-term (albedo, evapotranspiration, carbon dioxide flux) as well as long-term effects (transition in ecosystem, carbon dioxide flux, active-layer thickness). Effects of wildfires on ecology (vegetation changes and recovery), hydrology (soil moisture dynamics, surface energy balance) and physics (active-layer changes) on boreal ecosystems have been investigated. However, the hydrological impacts of wildfires on arctic tundra are less understood.

Meteorological stations with extensive soil instrumentation are operated on the Seward Peninsula in four locations. One of these stations was destroyed in a severe fire in August 2002, resulting in a loss of instrumentation. This created, however, a unique opportunity to monitor the changes of this arctic tundra system following a fire. The damaged equipment was replaced within a few months. A nearly continuous four-year record before, and almost one year of measurements after the fire has been collected.

The impact of fire on an arctic tundra ecosystem with respect to surface energy balance, subsurface thermal regime, and soil moisture dynamics is being investigated. The study characterizes the influence of burn severity on short-term impacts and consequences for long-term recovery. Additional distributed measurements of subsurface moisture and temperature are utilized to investigate the influence of burn severity. Preliminary results will be presented.

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Laboratory-Based Studies of the Physical and Biological Properties of Sea Ice: A Tool for Understanding Physical Processes and Feedback Mechanisms in the Arctic

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Laboratory-based studies of the physical and biological properties of sea ice are an essential tool for understanding interactions between the structure of the ice, the biological communities it supports, and the partitioning of shortwave radiation at the atmosphere-ice-ocean interfaces. Environmentally controlled studies promote improved understanding of the impact of climatic variability on sea ice properties and ice-dependent ecological processes. Experiments spanning a wide range of environmental conditions can help identify feedback mechanisms between physical and biological processes and their response to climate fluctuations, both established and postulated.

Climatically sensitive processes that occur across the atmosphere-ice-ocean interfaces can determine surface radiative energy fluxes and the transfer of nutrients and mass across these boundaries. High temporally and spatially resolved laboratory analyses over a wide range of environmental conditions lend insight to the physics that drive these transfer processes. Sensitive detection techniques and in situ measurements not feasible in the field can be used to study natural sea ice core samples and laboratory-grown ice. Such experiments yield insight on small-scale processes from the microscopic to the meter scale and can be powerful interdisciplinary tools.

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Improving Arctic Snow-related Features Within Regional Climate Models

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Regional climate models currently being applied to the Arctic typically use relatively simple snow energy- and mass-balance accounting procedures for their snow evolution representations. Three snow-related deficiencies have been identified that are generally common among these models. These are: 1) unrealistic subgrid-scale snow distribution representations, 2) no accounting for blowing-snow sublimation, and 3) an oversimplified representation of snow-vegetation interactions.

To develop parameterizations or submodels to correct these three deficiencies, and their interactions with each other, we have implemented a collection of field-based observations and off-line atmosphere-snow-vegetation interaction models. We used this collection of observations and models to improve our understanding of the governing Earth-system components, and to develop improved representations of those components and associated processes within the context of ClimRAMS, a climate version of the Regional Atmospheric Modeling System (RAMS). Testing and validation simulations were performed over Northwestern Alaska. Ultimately, the improved modeling system will be able to address issues related to potential future arctic climate system changes, such as regional temperature and precipitation changes, and increases in arctic shrub stature and abundance.

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Assimilation of Satellite Ice Concentration Data in a Coupled Ice-Ocean Model for the Arctic Ocean, Using the Ensemble Kalman Filter

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Climate modeling allows to determine, analyse, and forecast climate variability. However, for model forcing, running, and validation one needs various input data. Such data can be provided by in situ and remote measurements. In many cases, satellite sensors provide needed data of temporal and spatial resolutions and coverage. Moreover, satellite data can be used for model performance improvement using assimilation procedures that provide integration of satellite and any other observational data into numerical models.

Sea ice is an important component of the high-latitude climate system. The presence of sea ice significantly affects the sea surface density, and exchanges of heat, moisture, and momentum between the ocean and atmosphere. Assimilation of sea ice concentrations in coupled ice-ocean model is an interesting approach to improving model results affected by deficiencies (e.g., model resolution and model physics), which should make forecasts more reliable.

An implementation of the Ensemble Kalman Filter (EnKF) with a coupled ice-ocean model is presented in this study. The model system consists of the HYbrid Coordinate Ocean Model (HYCOM) coupled with a dynamic-thermodynamic model using the Elastic-Viscous-Plastic (EVP) rheology. The observed variable is ice concentration from passive microwave sensor data (SSM/I).

The results have shown that the assimilation of ice concentration has the desired effect of reducing the difference between observations and model. Comparison of the assimilation experiment with a free-run experiment shows that there are large seasonal differences. The assimilation scheme provides updating other variables contained in state vector, such as ice thickness, ocean upper-layer temperature, and salinity. Assimilation has the strongest impact close to the ice edge, where it ensures a correct location of the ice edge throughout the simulation.

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Meeting and Mixing of Waters of the Arctic Ocean and the Nordic Seas North of Fram Strait and Along the East Greenland Current: Interpretations of the Arctic Ocean-02 *Oden* CTD Observations

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As a part of the Arctic Ocean 2002 programme, the Swedish ice breaker *Oden*, in spring, made an oceanographic survey of the East Greenland Current from north of Fram Strait to south of Denmark Strait, while RV *Knorr* of Woods Hole operated in the ice free parts of the Greenland, Iceland, and Norwegian Seas. The work on *Oden* concentrated on water mass processes in ice-covered waters and on the interactions between the waters of the Arctic Ocean and the Nordic Seas. The CTD observations made on *Oden* are discussed.

The observations show the formation of dense bottom water in Storfjorden; the cooling of Atlantic water entering the Arctic Ocean; the formation of the embryo halocline water by the melting of sea ice on top of the Atlantic inflow; the meeting and mixing of arctic and Nordic seas water masses in Fram Strait; the evolution of the East Greenland Current along the Greenland continental slope; and changes in the overflow plume as it sinks down the slope into the deep Irminger Sea.

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The Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Project

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Recent measurements in the Arctic and in Antarctica indicate that there is significant chemical species exchange between snowpacks, sea ice, and the atmosphere. A number of highly photochemically active gases (e.g., formaldehyde, oxides of nitrogen, and molecular halogens) are emitted from sunlit snowpacks into the overlying atmosphere. These species are important free radical precursors that influence the oxidizing capacity of the atmosphere. The emission of molecular halogens is believed to initiate a halgen-atom mediated chain reaction that destroys lower atmospheric ozone at the time of polar sunrise.

Research to understand surface ozone depletion chemistry led to the discovery that it is perturbing the biogeochemical cycle of many elements such as mercury, and that ozone depletion chemistry is likely to have a significant impact on radiative transfer in the atmospheric layer near the surface, with important consequences on the air-sea exchange of biologically mediated compounds. Although we have learned much in the past 5–10 years, this area of inquiry still represents one of substantial unknowns and environmental importance. A workshop was conducted in November of 2002, aimed at addressing the state of this area of inquiry, and to delineate the current important unknowns. This workshop has led to the development of a new project aimed at studies of Ocean-Atmosphere-Sea Ice-Snowpack interactions in the Arctic, known as OASIS. In this presentation, we will discuss the science and objectives of OASIS, as currently defined.

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Possible Feedbacks on Arctic Cloud Formation: Can the Arctic Biosphere Affect the Melting of the Ice?

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Boundary layer clouds are an important factor affecting the energy balance at the surface in the Arctic. In contrast to the mid-latitude oceans, low-level clouds are a warming factor for the Arctic Ocean through most of the year. During winter, the effects of low-level clouds are the single most important local factor determining the stability of the lower troposphere. Clouds modulate the energy balance at the surface with amplitudes far larger than those imposed by an enhanced greenhouse effect. In summer, with larger cloud fractions, changes in the microphysics of clouds—more small, or fewer large droplets—can alter their radiative properties for solar radiation. Formation of clouds requires the presence of small airborne particles, Cloud Condensation Nuclei or CCN. While the amount of water in a cloud is determined by the thermodynamic and dynamic properties of the atmosphere (e.g., temperature, moisture, and vertical motions and mixing), the number of droplets is regulated by the abundance of CCN. With many CCN the condensed water is distributed over many small droplets, rather than over a few large ones. This in turn makes the cloud look “whiter,” thus reflecting more solar radiation back to space.

Where then do these particles come from? There are obviously anthropogenic sources, related to burning of fossil fuels. Such sources are mainly located in industrial areas at large distances from the central Arctic. There are also natural sources; for example, breaking wind-driven ocean waves generate a spray of sea-salt particles that are effective CCN. These are probably of smaller importance in the central Arctic, since the fraction of open sea is small. A large natural source is due to biological activity: grazing of algae by zooplankton generate a gas called DMS; its sulfur becomes oxidized in the atmosphere to sulfate particles. The latter is a dominant source in the summertime arctic marginal ice zone. However, as these particles become CCN while traveling in over the pack ice, they will become parts of cloud droplets that eventually are deposited at the surface by gravitational settling or precipitation, and the particles are lost forever. The farther in over the pack ice the air gets, the less CCN remain in the air, which affects the properties of arctic clouds, making them “grayer” than their mid-latitude counterparts. These processes are poorly described in current climate models.

Can climate change alter the arctic system such that more biogenic particles are produced locally by, for example, opening larger areas of open water? Are there other processes that produce biogenic aerosols locally? Will such an enhanced local production of CCN in the central Arctic Ocean act as a negative feedback, producing brighter clouds that reflect more solar radiation back to space? The Arctic Ocean Experiment 2001 (AOE-2001) on the Swedish icebreaker *Oden* was launched to take in situ measurements of atmospheric chemistry, aerosols, and boundary-layer structure during summer 2001, to help answer these questions. We found clear evidence that local aerosol production at the ocean surface occurred even when the ice fraction was rather large. In addition to formation of new, very small particles, we also found evidence of new and moderately large aerosols direct from open leads, containing bacteria and viruses. These were very similar to particles sampled from the biogenic surface film on the open leads. The boundary-layer structure was also relatively well mixed in the lowest 100s of meters, but often capped by a very strong inversion. This would facilitate mixing of surface-generated aerosols through the boundary layer, but inhibit entrainment of aerosols or aerosol precursor gases from distant sources, long-range transported in the free troposphere.

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DOE-ARM Science at the North Slope of Alaska Site

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With the database of measurements from the DOE-ARM NSA/AAO expanding, this high-quality, now five-year long data stream is increasingly being used by the ARM science community to study questions related to arctic climate. The primary focus of the ARM community is on clouds and the processes impacting them. We will show results from ARM studies documenting abrupt changes in (liquid) cloud properties in the late spring; difficulties of the operational models (NCAP, ECMWF) to accurately represent low-level cloud properties; and statistical studies relating synoptic conditions to cloud field properties.

The DOE-ARM program will conduct a focused field campaign in October 2003 to investigate several questions related to mixed-phase clouds in the Arctic. The primary objectives for the Mixed-Phase Arctic Clouds Experiment (M-PACE) will be to increase our understanding of these clouds, common in the arctic, and to develop retrieval algorithms for mixed-phase clouds. Secondary objectives are related to radiative transfer processes and how we can model them.

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The Expanded Regional Integrated Monitoring System (E-RIMS) for Pan-Arctic Water System Studies: Project Overview

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The arctic system and its water cycle play a central role in regulating Earth's climate and biogeochemistry. The Arctic is also experiencing rapid environmental change, several elements of which are associated with the hydrological cycle. The Expanded Arctic Regional Integrated Monitoring System (E-RIMS) links an existing hydrological monitoring system for the arctic landmass to an Arctic Ocean component. The program focuses on carrying out studies of variability in the pan-arctic water cycle and of linkages among major system components.

The E-RIMS framework builds on earlier work to develop a consolidated biogeophysical data and integration tool compendium. The E-RMIS emphasizes: (a) use of improved numerical weather prediction model (NWP) fields, (b) a major expansion of near real-time river mouth hydrographic stations to include new upstream holdings, (c) a river temperature model and data for terrestrial heat inputs to the ocean, (d) ice sheet/glacial meltwater estimates, (e) an ocean-ice-atmosphere model, (f) a formal space-time variability analysis, and (g) water budget closure for the full system, with statistical analysis of error. The time frame of E-RIMS is both historical (from 1960) and near real-time.

The science driving this work seeks to more fully characterize variability in the pan-arctic atmosphere-land mass-ocean freshwater system. The linked models are being used to examine the origin of freshwater fluxes in the atmosphere and landmass and how water is then partitioned between solid (sea ice) and liquid forms in the ocean. E-RIMS will also examine freshwater processing over the shelf, export from the shelf, storage in the basins, and ultimately, export into the North Atlantic Ocean. An overview of the principal elements of E-RIMS will be discussed, and an early application of the system to estimate closure of the pan-arctic water budget will be presented. The role of such studies in the broader context of the Freshwater Initiative (FWI) is also discussed.

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A Coupled Ice-Ocean Model in the Pan Arctic and North Atlantic Ocean: Part 1: Simulations of Seasonal Cycles

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A coupled ice-ocean model (CIOM) is configured for the pan-Arctic and North Atlantic Ocean (PANAO) with a 27.5 km resolution. The model is driven by the daily atmospheric climatology averaged from the forty-year NCEP reanalysis (1958–1997). The ocean model is the Princeton Ocean Model (POM), while the sea ice model is based on a full thermodynamical and dynamical model with plastic-viscous rheology. A sea ice model with multiple categories of sea ice thickness is utilized. We first focus on seasonal cycles of sea ice and ocean circulation. This model reasonably reproduces seasonal cycles of both the sea ice and the ocean. Climatological sea ice areas derived from historical data are used to validate the ice model performance. The simulated sea ice cover reaches a maximum of 14 x 10^6 km^2 in winter and a minimum of 6.7 x 10^6 km^2 in summer, which are close to the ninety-five-year climatology with a maximum of 13.3 x 10^6 km^2 in winter and a minimum of 7 x 10^6 km^2 in summer. The simulated general circulation in the Arctic Ocean, the GIN seas, and northern North Atlantic Ocean are qualitatively consistent with historical mapping. We found that the winter low salinity or freshwater content in the Canada Basin tends to converge due to the strong anticyclonic atmospheric circulation that drives the anticyclonic ocean surface current, while summer low salinity or freshwater tends to spread inside the Arctic and exports out of the Arctic, due to the relaxing wind field. It is also found that the warm, saline Atlantic Water intrudes farther into the Arctic in winter than summer due to prevailing winter wind stress over the northern North Atlantic that is controlled by the Icelandic Low. Seasonal cycles of temperature and salinity at several selected representative locations reveal regional features that characterize different water mass properties.

The CIOM is applied to examine the response of the ice-ocean system to Arctic Oscillation (AO) forcing and Dipole forcing (DF). It is found that the AO leads to subsurface seawater temperature seesaw between the Barents Sea and the Labrador Sea, while the DF is the major cause of driving sea ice export out of the Arctic Basin, instead of the AO. Observations support the two new findings.

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Exchanges Between the Arctic and Atlantic Oceans in a Global Ice–Ocean Model

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A retrospective investigation is conducted to examine the variability of heat and mass exchanges between the Arctic and Atlantic oceans over the past fifty years using a parallel ocean and ice model (POIM). The POIM is global; its model grid emphasizes the Arctic Ocean and its linkages to the Atlantic Ocean. Model results indicate that the transports of water and heat at Fram Strait, Denmark Strait, and the Faroe-Shetland Passage are correlated significantly with the North Atlantic Oscillation index. So are water outflow at the Canadian Archipelago channels and ice exports at Fram Strait and Denmark Strait. There is a noticeable positive trend in northward heat transport in the Greenland, Iceland, and Labrador Seas over the period of 1953–2002, while there is a negative trend in freshwater outflow at Denmark Strait and freshwater inflow at the Faroe-Shetland Passage.

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DRIVERS AND CAUSES: PRESENTATIONS

Stratosphere/Troposphere Coupling and Effects on High-Latitude Climate

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Variability in the stratosphere is driven mainly by planetary-scale waves that originate in the troposphere, but there are feedbacks in which the tropospheric circulation is affected by conditions in the stratosphere. These feedbacks are important on two time scales: intraseasonal and long-term trends. Over periods of one week to two months, observations show a strong statistical relationship between circulation anomalies in the lowermost stratosphere and changes to the phase of the Arctic Oscillation at Earth's surface. Following changes to the circulation of the lowermost stratosphere, the Arctic Oscillation tends to be biased for up to two months, affecting high-latitude temperatures and winds. The effect only happens during the extended winter season, when planetary-scale waves are able to create large circulation anomalies in the stratosphere.

If the stratospheric circulation changes due to increasing greenhouse gases, ozone loss, or other effects, how will the troposphere be affected? In the Southern Hemisphere there is strong evidence from observations and models that human-induced ozone depletion has already altered the surface climate of Antarctica during late spring and summer. In the Arctic, climate models disagree as to how the circulation of the stratosphere will change, but it is becoming clear that changes to the stratosphere will be felt at the surface.

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Arctic Ocean Change: What Changes and What Doesn't (Almost)

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Change is considered in three layers: 1) the marine cryosphere and ocean-mixing layer, 2) the main halocline, and 3) below the halocline. Changes in 1 and 2 can be understood in responses to changing windstress and thermodynamic forcing. Changes in the subhalocline 3 are more challenging, as water properties exhibit large changes over inter-annual time scales while circulation is almost unaltered. These changes partly reflect varying upstream conditions and air-sea fluxes over the Barents Sea. Although subhalocline circulation is surprisingly persistent, there are important but subtle changes at only a few key diffluence points where deeper flows are affected by variations in halocline thickness. Water properties then change markedly despite a subhalocline circulation that is nearly unchanging.

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Solar-Induced Cyclic Variations of Holocene Climate and Ecosystems in a High-Latitude Region of the North Pacific

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Small variations in solar output appear to have played a prominent role in the Holocene dynamics of the Earth's climate system. Although the mechanisms for sun-climate linkages at sub-Milankovitch time scales remain a focus of debate, evidence is emerging in proxy records from various regions. In the sub-polar region of the North Pacific, there exist numerous published records of Holocene climatic change, but they all lack the temporal resolution adequate to detect solar-induced climatic variations at centennial scales.

We present here a continuous, multi-decadal record of Holocene environmental change in southwestern coastal Alaska. Analyses of lake sediment for biogenic silica, organic carbon and nitrogen, pollen assemblages, diatom oxygen isotopes, and compound-specific hydrogen isotopes reveal marked changes in effective moisture, aquatic productivity, and terrestrial vegetation. These variations occurred with periodicities of ~200, ~450, and ~950 years, similar to those of solar activity. Furthermore, they appear to be generally coherent with time series of the cosmogenic nuclides ^{14}C and ^{10}Be as well as North-Atlantic drift ice. Our results imply that weak solar variations induced pronounced cyclic changes in northern high-latitude environments. They also provide evidence that centennial-scale shifts in the Holocene climate were similar between the subpolar regions of the North Atlantic and North Pacific, possibly because of sun-ocean-climate linkages.

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The Ecology and Paleoecology of Human-Landscape Interactions on the North Pacific and Southern Bering Sea: Investigating the Role of the Aleut as Ecosystem Engineers

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Ten years of research on the western Alaska Peninsula have resulted in a massive paleo-ecological and ecological data set spanning the past 5,000 years. Nearly 100,000 bird, mammal, and fish bones, extensive samples of shellfish, six pollen cores, terrestrial and intertidal ecological studies, ethnographic interviews, and a complete coastal geomorphic reconstruction, provide data critical to our understanding of the long-term dynamics of the southern Bering Sea and North Pacific ecosystems. When combined with other regional proxy records, these data allow a detailed reconstruction of changes in the marine and terrestrial environments, changes in long-term cycles of species abundance, and changes in the geographic distributions of key species. Ultimately, these data are the foundation for the development of models for the investigation of the critical role indigenous peoples played in the engineering of northern marine ecosystems. This paper represents a transdisciplinary approach by placing humans as a critical component of the structure of marine and shoreline environments in the north.

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Towards a Regional Arctic Climate Model for SEARCH

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Two of the primary hypotheses of SEARCH state that changes in the Arctic are interrelated and that feedbacks exist between local and large scales within the arctic system as well as between the arctic and global systems. Both hypotheses point to the importance of complex linkages among arctic climate components. The pan-arctic atmospheric circulation and in particular its variability is considered to be the critical driver of such changes. It has been demonstrated that this variability is associated with the hemispheric if not global atmosphere dynamics. At the same time, ocean-sea ice-atmosphere interactions and feedbacks in the Arctic must be considered as well, for their impact on climate, possibly at longer (i.e., inter-annual to decadal) time scales. Observational understanding of such processes, e.g., during the Surface Heat Budget of the Arctic Ocean (SHEBA) program, has been limited both in time and space. On the other hand, global climate models are not yet ready to adequately address such issues because of their generally crude representation of the arctic region and often their non-arctic focus.

In this talk, we make a case for a regional arctic climate model, consisting of state-of-the-art atmosphere, ocean, sea ice, and land components, utilizing the available modern computer technology, and coordinated with the ongoing and planned observations to address some of the main SEARCH goals. We report on the progress in modeling the Arctic Ocean and sea ice, outline an approach for the development of a regional climate model and discuss possible benefits to the SEARCH program and to other research, commercial, and defense activities associated with the Arctic Ocean. The timeliness of such an effort within the SEARCH program and its potential for short-term arctic climate predictions are emphasized.

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Relationships Between Understanding Unaami and Predicting the Arctic System

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During the second half of the 20th century, the arctic system experienced changes of practical and statistical significance on time scales of approximately five to thirty years. Measurements, analyses, and publications concerning these changes are distributed unevenly among the scientific disciplines, and across the sub-domains of the arctic system. For example, studies of change in the physical environment far outnumber the studies of change in the economic, social, and cultural subsystems. And in the physical environmental sciences, studies of the atmospheric sub-domain are more numerous than studies of the oceanic and terrestrial sub-domains.

Nevertheless, the SEARCH Science Plan builds a case that major elements of recent arctic change are related across domains and disciplinary boundaries, and this suite of related changes is termed "Unaami." The plan goes on to hypothesize that Unaami is a component of climate change, and that the physical manifestation of Unaami has large impacts on ecosystems and people in the Arctic. If so, then it is important to assess the contribution of Unaami to the *predictable* portion of climate change, and to determine the extent to which the physical Unaami's impacts may be inferred from past observations. Here we explore these two aspects of the problem, drawing on published papers and existing data sets, and attempting to identify critical problems and gaps in theory, observations, and analysis that limit or qualify conclusions about prediction. Some implications for SEARCH planning are discussed.

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Searching for Bellwethers in Changing Arctic Environments: Some Cautionary Notes

David W. Norton Arctic Rim Research

An instructive dose of humility is within reach of investigators able to recall the scientific preoccupation with "nuclear winter" in the mid-1980s and willing to compare that with the current focus upon environmental arctic change. A discrete change in any single environmental parameter can produce contradictory responses, especially by biological systems. The history of blue mussels' (*Mytilus edulis* complex) occupation of arctic nearshore marine habitats over the most recent 18,000 years (of ~2.5 million years of the genus' fossil record in the Arctic) illustrates how easy it is to attribute observed changes in a biological system to environmental factors that are not directly causal. These mollusks offer several further cautionary lessons. Since the mid-20th century, for example, scientists' observational coverage, and publishing Western arctic findings have left significant gaps, coincident with removal of natural history as a systematic enterprise from public support. Logistics and other specializations separating deepwater oceanographers from aquatic and terrestrial scientists tend to orphan arctic coastal and estuarine environments. Under the heading of predicting the effects of environmental arctic change, recent nearshore sea ice studies supported by the NSF HARC initiative remind us how poorly we have understood late winter motions by ice floes within 1–100 km of the Chukchi Sea coast—a technological problem has perpetuated gaps in geographic scales of measurements. Temporal scales are no less problematic. The diverse arctic dinosaur fauna now known to have persisted for at least the final 30 million years of the Mesozoic (Cretaceous) in and beyond northern Alaska strains our grasp of the "Arctic-ness" of high latitudes in the absence of extreme seasonality and perennial ice. Further cautionary parables are introduced from experience with NOAA-supported chemical and human ecology studies in several arctic communities of the Western Arctic, wherein investigators collaborating with arctic residents have learned to phrase questions carefully.

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Arctic Ocean and Sea Ice Changes, Greenhouse Forcing and the Arctic Oscillation

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Recent changes observed in the Arctic Ocean and sea ice are coincident with the decreasing trend in arctic pressures and the positive phase of the Arctic Oscillation. These changes are also consistent with the climatic warming in response to increasing greenhouse gases. The pattern of sea ice drift has shown a shrinking of the anticyclonic Beaufort Gyre and greater cyclonic circulation in the Eurasian Basin after 1988. Warmer subsurface ocean temperatures in the Amundsen and Markhov Basins observed in the early 1990s indicate a greater extent of Atlantic-layer water and a retreat of the cold halocline.

The speculated cause of this Atlantic-layer warming is the increased inflow via the Barents Sea and Fram Strait, driven by stronger and warmer northward wind forcing in the Greenland-Iceland-Norwegian (GIN) Seas. Experiments with an arctic ice and ocean model suggest that the atmospheric circulation patterns since 1988 have driven the increasing influx of warmer, saltier Atlantic water into the Arctic. Climate simulations with a global atmosphere-ice-ocean climate model that include both the forcing from increasing greenhouse gases and natural forcing are used to investigate the response of the arctic sea ice and ocean to present-day global climate changes. The response of the ice and ocean to the Arctic Oscillation simulation from the climate model is compared to that produced by the greenhouse forcing. The contribution of the changes in ice and ocean waters from both the AO and from greenhouse forcing can be determined independently from these climate simulations.

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Fresh Water Content Variability in the Arctic Ocean

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Arctic Ocean model simulations have revealed that the Arctic Ocean has a basin-wide oscillation with cyclonic and anticyclonic circulation anomalies (Arctic Ocean Oscillation; AOO) which has a prominent decadal variability (Proshutinsky and Johnson, 1997). This study explores how the simulated AOO affects the Arctic Ocean stratification and its relationship to the sea ice cover variations. The simulation uses the Princeton Ocean Model coupled to sea ice (Hakkinen and Mellor, 1992; Hakkinen, 1999). The surface forcing is based on NCEP-NCAR Reanalysis and its climatology, of which the latter is used to force the model spin-up phase.

Our focus is to investigate the competition between ocean dynamics and ice formation/melt on the Arctic Basin-wide fresh water balance. We find that changes in the Atlantic water inflow can explain almost all of the simulated fresh water anomalies in the main Arctic Basin. The Atlantic water inflow anomalies are an essential part of AOO, which is the wind driven barotropic response to the Arctic Oscillation (AO). The baroclinic response to AO, such as Ekman pumping in the Beaufort Gyre, and ice melt/freeze anomalies in response to AO are less significant considering the whole arctic freshwater balance.

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Holocene Thermal Maximum in the Western Arctic

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One overall goal of NSF-PARCS (Paleoenvironmental Arctic Science) research is to contribute to the understanding of the nature and consequences of warmth in the Arctic and its impact on the global climate system. An immediate objective is to describe the state of the Arctic when it shifted toward, and experienced, warmer conditions during the Holocene (the present interglacial period). During the early to middle Holocene, much of the Arctic experienced warmer-than-present (20th century) temperatures, but the warming occurred at different times and to varying degrees in different places. The pattern of this variability can be examined to understand how climate in the Arctic responded to radiative forcing driven by changes in insolation and other factors. By characterizing the pattern of early Holocene warming, we can hypothesize possible mechanisms that underlie the heterogeneity of the observed response to forcing. Such mechanisms reflect the particular geography of the Arctic and its feedback processes that might influence the pattern and magnitude of potential future changes. The spatial pattern of the HTM can, for example, be compared with the observed pattern of recent warming, and with the characteristic signatures of modes of variability known from the instrumental record.

As the first step in addressing this objective, the PARCS working group on the Holocene thermal maximum has compiled a database of published and unpublished records of Holocene paleoenvironmental change in the Arctic. The spatio-temporal pattern of peak Holocene warmth (Holocene thermal maximum, HTM) was traced over 140 sites across the western hemisphere of the Arctic (0° to 180°W; north of ~60°N). Paleoclimate inferences based on data from a variety of sources (lake and marine sediment, peat, and glacier ice) and proxies (pollen, macrofossils, chironomids, diatoms, geochemistry, oxygen isotopes, etc.) provide clear evidence for warmer-than-present conditions at 120 of these sites. At the sixteen terrestrial sites where quantitative estimates have been obtained, local HTM temperatures (primarily summer estimates) were on average 1.6° ± 0.8°C higher than present (approximate average of the 20th century), but the warming was time-transgressive across the western Arctic.

As the precession-driven summer insolation anomaly peaked 12–10 ka (thousands of calendar years ago), warming was concentrated in northwest North America, while cool conditions lingered in the northeast. Alaska and northwest Canada experienced the HTM between ca. 11 and 9 ka, about 4,000 years prior to the HTM in northeast Canada. The delayed warming in Quebec and Labrador was linked to the residual Laurentide Ice Sheet, which chilled the region through its impact on surface energy balance and ocean circulation. The lingering ice also attests to the inherent asymmetry of atmospheric and oceanic circulation that predisposes the region to glaciation and modulates the pattern of climatic change. The spatial asymmetry of warming during the HTM resembles the pattern of warming observed in the Arctic over the past several decades.

Although the two warmings are described at different temporal scales, and the HTM was additionally affected by the residual Laurentide ice, the similarities suggest there might be a preferred mode of variability in the atmospheric circulation that generates a recurrent pattern of warming under positive radiative forcing. Unlike the HTM, however, future warming will not be counterbalanced by the cooling effect of a residual North American ice sheet.

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Preliminary Volume Transports through Nares Strait, Summer 2003

Andreas Muenchow University of Delaware

In 1853, Elisha Kane reported on a generally southward drift of ice from the Arctic into Baffin Bay in what would later be named Nares Strait. Little did he know that the southward transport of freshwater between Greenland and Ellesmere Island impacts ocean circulation and climate over the North Atlantic at decadal, centennial, and longer time scales. Here I present preliminary transport estimates of the oceanic flow through Nares Strait.

In the summer of 2003 the USCGC *Healy* surveyed the area with a 75-kHz acoustic Doppler current profiler (ADCP). This sonar estimates velocity vectors from 25-m to 400-m depth once every four seconds along the ship's track. It provides synoptic transport and flux estimates across the 35-km wide and 350-m deep channel. The data precede future estimates of fresh-water flux, derived from a mooring array deployed this summer, that consists of seven ADCPs, eight CT/CTD strings, two ice-profiling sonars, and five tide gauges. The vessel-mounted ADCP data constitute the only regional velocity observations resolving the crucial internal deformation radius.

In the summer of 2003, we find persistently average flows are southward, reaching up to 0.5 m/s with substantial vertical and lateral variability. This mean flow generally opposes winds from the south. In both the ocean and atmosphere, we find strong lateral and vertical variability. This variability may not always resemble the larger, synoptic-scale, geostrophic expectations. Our observing array is ideally suited to investigate one possible pathway and dynamics of a recent, ~5 $km^{3,}$ abrupt, "breaking-dam" type freshwater release from Disraeli Fjord, associated with the partial breakup of the Ward Hunt ice shelf just upstream from our observing array.

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Changes in the Presence of Mussels (*Mytilus* spp.) and Macroalgae in Arctic Alaska: Re-evaluating Evidence used to Relate Bivalve Presence to Climate Change

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Live mussels, attached to fresh laminarioid brown algae, all fastened to clusters of pebbles and small cobbles, were repeatedly cast ashore by autumn storms at Barrow, Alaska, in the 1990s. Specimens of *Laminaria saccharina* and *L. solidungula* shorten by 100 km a 500-km gap (Peard Bay to Stefansson Sound) between previously known concentrations of these species of kelp.

For the genus *Mytilus*, a 1,600-km gap in fully documented locations existed between Kivalina in the southern Chukchi Sea and the Mackenzie River delta. Live mussels and macroalgae were neither washed up by storms nor collected by active biological sampling during extensive benthic surveys at Barrow in 1948–50. Contrary to initial expectations, we cannot interpret the current presence of these bivalves and macrophytes as arctic range extensions due to warming, analogous to those manifested by tree line in terrestrial systems and Pacific salmon in marine environments. Supplemental information and critical evaluation of survey strategies and rationales make rising sea temperatures an unlikely cause. Alternative explanations focus on past seafloor disturbances, dispersal from marine or estuarine refugia, and effects of predators on colonists. This review suggests refining some interpretations of environmental change that are based on the extensive resource of Cenozoic fossils of arctic mollusks.

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Velocity Estimates for Ice Drifting in Alaska's Northern Chukchi Sea Flaw Zone During Spring Subsistence Whaling Seasons of 2000 and 2001: Climate Change Implications?

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By late winter each year, coastal sea ice in Alaska's northern Chukchi Sea consists of shorefast ice and moving ice floes from immediately beyond fast ice, out some 100 km to coherent pack ice. Because coastal resistance to westward-drifting polar pack ice decreases west of Point Barrow, a semi-permanent polynya or flaw zone dominates coastal ice in this region. Iñupiat residents capitalize on the alongshore flaw lead of open water to hunt migrating bowhead whales from shorefast ice from mid-April to early June.

Although Iñupiat understand ice motions beyond their horizon, the northern Chukchi Sea flaw zone has received less scientific attention than either polar pack ice farther offshore, or seasonal shorefast ice. Technology—chiefly synthetic aperture radar (SAR) satellite imagery—to address ice movement at a spatial scale familiar to traditional hunters has become available relatively recently. Ice movement differed radically between the two field seasons of this study, illustrating the contrasts between optimal and unsatisfactory conditions for spring whaling at Barrow. Adequate prediction of ice integrity and its public safety implications in the northern Chukchi Sea is projected by this analysis to require conceptual refinements to our current understanding, including:

a) recognition of the dominant role played by the flaw zone;
b) replacing a focus on ship safety in ice-dominated waters with concern for ice integrity in high-energy environments; and
c) chronicling ice motions through remote sensing of additional March–June periods.

Cause-effect connections are explored through case studies of ice floe accelerations, in which the influences of seafloor, water column, ice, and meteorological conditions are evaluated integratively over time.

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Surface Energy Budget Requirements for Pack Ice Change Attribution During SEARCH

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Understanding changes in the mass balance of the arctic pack ice is a key component of the Study for Environmental Arctic Change (SEARCH), and the surface energy budget (SEB) determines the mass balance of a particular floe. A simple definition of the SEB is: $F_{tot} = Q^* - H_s - H_l + C$, (1) where F_{tot} is the total energy flux into the surface slab, Q* the net radiative flux, H_s the turbulent sensible heat flux, H_l the turbulent latent heat flux, and C the conductive flux. To understand the causes for the changes in the mass balance, each of the components of the SEB needs to be monitored in addition to the mass balance itself. The following questions are important for deciding on how to monitor the SEB: 1) what are the major contributors to changes in F_{tot}, 2) how accurately do we need to know each term, and 3) how accurately can we measure each term with a) surface measurements and b) satellite measurements? Some of the analyses from SHEBA (Persson et al. 2002) and satellite studies by Key et al (1997) and others can be used to try to answer these questions.

The SHEBA measurements show that F_{tot} can undergo changes of 60 Wm^{-2} or greater in a matter of a few hours, and that each of the terms on the right-hand-side of (1) can have similar variations. These rapid changes can happen during both winter and summer, and are often associated with synoptic or mesoscale atmospheric disturbances that produce clouds, wind, and precipitation. This frequent and large variability of all terms suggests that the measurements of the terms should be made greater than once per day, and that none of the terms can be ignored.

However, dependencies between the terms may make their estimation easier. For instance, wintertime clouds (clear skies) generally produce near-zero (-40 Wm^{-2}) Q*, small positive (large negative) H_s, and small (large) positive C. Studies of the SHEBA data set should explore these dependencies further and how they can be utilized in improving satellite estimates of the terms.

The mass balance and SEB measurements at SHEBA can be used to address questions 2) and 3). The SHEBA surface ablation of 0.88 m ice equivalent implies an annual mean F_{tot} of +8.4 Wm^{-2}. Considering the uncertainties in the measurements and in crucial parameters such as the thermal conductivity of snow, the observed annual mean F_{tot} was in the range 4.0–11.0 Wm^{-2}. Further consideration of the surface viewed by the radiometers and the best estimate of the biases, the best estimate for the observed F_{tot} was 8.2 Wm^{-2}, remarkably close to that implied by the surface ablation. During the annual cycle, the pack ice typically has a net mass loss at the surface and a mass gain on its underside. A balance between the surface ablation and bottom accretion would have required a surface ablation of only 0.53 m ice equivalent, implying an equilibrium annual mean F_{tot} of +5.1 Wm^{-2}. Hence, even in this case of significant mass loss, the accuracy of the annual average F_{tot} needs to be better than 3.1 Wm^{-2} in order to discriminate between the actual conditions and the equilibrium conditions. The SHEBA data are only able to make this discrimination when the arguments for determining the “best estimate” are invoked. Equilibrium estimates using two model studies suggest that the required accuracy may be even more stringent than this simple calculation.

Extending the uncertainty estimates of Key et al. (1997) to the annual time scale, the uncertainty in satellite estimates of Q* is 1.4–2.9 Wm^{-2}, of comparable magnitude to the required accuracy in F_{tot} to discriminate conditions of significant mass loss. However, this satellite estimate assumes no biases in the satellite estimation technique, which Key et al. show is not a good assumption. Furthermore, these estimates do not consider estimating H_s, H_l, and C from satellites. Therefore, though satellite estimates of the SEB will be crucial for showing the spatial variation of the SEB terms, a handful of surface stations measuring the complete SEB and mass balance on the pack ice will be required to provide calibration of the satellite measurements and help remove biases in the satellite techniques.

Even with the surface stations, clear discrimination of the causes of mass balance changes is not guaranteed, as the SHEBA measurements suggest.

This exercise demonstrates that very careful attention needs to be paid to the accuracy of the surface and the satellite measurements if SEARCH is to be able to attribute observed pack ice changes to specific processes associated with the surface energy budget.

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A New Sea Ice Model for the Marginal Ice Zone

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Sea ice cover is a critical component of the arctic environment, largely controlling the energy exchange between the atmosphere and the ocean in the polar seas. Nowhere is this effect more dramatic than along the ice margins, where the abrupt transition from ice-covered to open seas gives rise to many processes, including deep convection and eddy formation, atmospheric instability generation, and time-variable brine and freshwater fluxes to the upper ocean. While most of the effort in ice modeling has been concerned with the pack ice in the high Arctic, in this paper we will present a new sea ice model that describes the formation, transport, and desalinization of frazil and pancake ice as it is formed in the marginal ice zone.

This marginal ice zone model (MIZMo) is currently under development for use at the National Ice Center in Washington, D.C. It is to be utilized as a tool to assist ice analysts in the production of operational ice charts for the world's oceans. The thermodynamics in the model are driven by the assimilation of daily ice concentrations determined from passive microwave data (SSM/I). Simulation results have been validated with field observations in both the Greenland and Barents Seas, and a salt flux model for the Greenland Sea has been developed.

Since nearly all sea ice initially forms in the ocean's surface layer as frazil ice, improving our understanding of this important process, and modeling its effects on the surface radiation and mass balances represents significant advancement in our understanding of the influence of this large-scale process on the polar climate system. The described marginal ice zone model can be utilized to calculate ice thickness, motion, brine rejection, and automatically detect the location of the ice edge on both historical data sets, as well as in a real-time "now-cast" mode.

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Monitoring Pan-Arctic Snowmelt Hydrology Using Active Radar

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Hydrological models that simulate the terrestrial water cycle at higher latitudes are dependent on accurate information regarding snowpack accumulation and melt. Melt is typically simulated using time series climate data which, given a sparse network of arctic meteorological stations, may not accurately capture the between-station variability. Remotely sensed estimates of pan-arctic snowpack freeze/thaw state offer the potential of more complete spatial coverage across large, remote areas.

We compared the timing of spring thaw determined from high-temporal resolution active radar data with basin runoff calculated from observed daily river discharge data for fifty-two sub-basins (5,000–10,000 km^2) across Canada and Alaska for the spring of 2,000. Algorithms for identifying initial thaw, primary thaw, and final thaw were applied to daily radar backscatter (~25 km resolution) from the SeaWinds scatterometer aboard NASA Quikscat. Radar-derived final thaw occurred close to the time of significant runoff increase in those sub-basins where sufficient snow was present (> ~5 cm SWE). Extending this analysis to the entire pan-arctic drainage basin, for which daily runoff must be interpolated from monthly runoff data, we related the correlations between remote sensing-derived final thaw and onset of snowmelt runoff to snowpack SWE, vegetation cover, and topographic complexity.

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Response of the Pan Arctic Ice-Ocean Climate to Atmospheric Circulation Regimes

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Using a coupled ice-ocean model developed by Wang et al. (2002), we investigate the responses of the Arctic Ocean climate (or ice-ocean system) to the Arctic Oscillation (AO) and the send mode (or so-called Barents Sea Oscillation, BO). Seven high AO index winters and six low AO index winters (similarly, the high and low BO index winters) were simulated by the coupled ice-ocean model under forcing provided by the NCEP/NCAR reanalysis. Statistical analyses and tests were applied to the composite differences between the high and low AO indices. For the high AO index phase that predominated during the 1990s, the results showed a reduction of sea ice in the Arctic Basin accompanied by an increase of sea ice in the Labrador Sea. This pattern resembles the North Atlantic Oscillation seesaw pattern (Roger and van Loon 1979; Wang et al. 1994). During the high AO phase, the arctic surface salinity increases and the surface temperature decreases, implying that more new ice was produced. The enhanced ice production is a consequence of greater ice export from the Arctic Ocean in response to anomalous cyclonic wind stress. From the subsurface layer to the Atlantic water layer, there is also a seesaw pattern in ocean temperature between the Barents and the Labrador Seas. During the high AO phase, the model reproduces the anomalous temperature intrusion of the Atlantic Water. While both the anomalous surface wind stress and the thermodynamical forcing contribute to sea ice and ocean variability, statistical analyses (EOF, regression, etc.) and significance tests (T-test and F-test) show that the wind stress accounts for a greater portion of these changes during the high AO phase than the thermodynamical forcing. We found that sea ice export is closely related to the BO, rather than the AO.

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SCIENCE MANAGEMENT, COORDINATION, AND RESOURCES: POSTERS

Toolik Field Station GIS: Spatial Information and Products for a Diversity of Clients

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Toolik Field Station, located at 68 degrees latitude on Alaska's North Slope, supports coordinated, multi-disciplinary, ecological research conducted since 1974 by scientists from around the globe. Geographic information is a critical component to, and a direct product of, this invaluable body of ecological knowledge and discovery. Understanding the complex relationships among ecosystem components is vastly augmented through a robust geographic database. Toolik GIS facilitates and expands research science through spatial data development, analyses, mapping, communication, and outreach, both within and beyond the Toolik community. The coordinated Toolik GIS database also extends the life and value of taxpayer-funded scientific data by expanding the applicability of those data to other projects, fostering collaboration, and by providing a context and distribution node for long-term legacy data. Toolik GIS also provides a conduit for the application of basic science toward improved landscape management through cooperative efforts and communication with state and federal management agencies.

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Fast Tactical Integration Console (Fast Tactic): Arctic Oceanographic Data Collection and Analysis for SEARCH

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Background
Historical arctic science data can be retrieved and analyzed from the Arctic System Science (ARCSS) Data Coordination Center (ADCC) and from a variety of other sources online and in hard copy as well as from various recording media such as CDs, tapes, and paper. SEARCH and arctic scientists will benefit greatly if all the data collected in ongoing arctic science efforts is easy to transfer to the ADCC in a simple electronic form. Fast Tactic provides the capability for an investigator to collect, store, retrieve and analyze data while at sea. Data storage can be either automatic or manual. By storing the data in the Fast Tactic relational database, the investigator can transfer that data more easily into the ADCC or other data storage systems on completion of a cruise.

If more timely exchange of the information is desired for purposes of analyzing data ashore, or to facilitate outreach activities related to science data collection in the field, the Fast Tactic data can be transmitted over satellite communications networks such as those already in use on USCG icebreakers or other arctic-capable science platforms.

Introduction
Fast Tactic is a laptop- or server-based system to automatically collect, process/edit, and use operational and environmental data on-board a ship, submarine, or other platform such as an AUV or buoy. It is designed to store, retrieve, and display ship-collected, historical, and gridded environmental data using a geographic information system which combines a Java Graphical User Interface and a relational database. New data may be compared to historical data from the same geographic area and time period. FAST TACTIC allows a quick analysis of available historical data to locate data gaps in either time or space to make cruise plans that can fill those gaps. Fast Tactic performs the following tasks:

- Plot ownship, historical, and gridded-database vertical profile (point) data (e.g., from CTDs, XBTs, sound velocity sensors);
- Plot along-track data (e.g., sound velocity, bathymetry, sediment thickness, ice thickness);
- Compare cruise or other platform-collected data and historical data (preloaded from the ADCC or other sources before the cruise);
- Generate statistics to determine if data are within normal bounds;
- Automatically extract profiles when a submarine, buoy, or UUV conducts a depth change.

By providing access to all data acquired within a cruise, the user is able to synthesize a broad picture of a survey area. When a ship loiters in a particular region, the Fast Tactic graphical displays enable the user to see how the environment changes over time and across the region. A statistics function summarizes environmental conditions for mission/cruise reports.

Fast Tactic has been successfully installed on two U.S. Navy submarines. In each installation, ownship sensor data were automatically extracted from an existing local area network.

Fast Tactic Key Capabilities
Fast Tactic provides the following key capabilities:

- Easy access to and display of current and past data;
- Automated data storage in a relational database (facilitates post-cruise data handoff);
- Comparison of various data sources is made simple;
- Visual and numerical data presentation.

Manipulation of Fast Tactic displays is simple: selection of parameters for display on a chart/graph is made with the mouse, without typing on the keyboard.

Demonstration System - SOARED
A demonstration system, called the Submarine Operational And Research Environmental Database (SOARED) is provided at http://wood.jhuapl.edu/soared. SOARED is populated with the following publicly available arctic data sets:

- Science Ice Exercise (SCICEX) ‘95 CTD Data
- National Oceanographic Data Center (NODC)

Historical CTDs
- Generalized Digital Environmental Model (GDEM) winter and spring temperature, salinity, and sound speed [Note - the GDEM data are sub-sampled to a 30-nmi grid to compensate for the approach to the North Pole, where five minutes of longitude asymptote to zero nautical mile spacing]
- SCICEX '95 Bathymetry (sampled once/minute)
- SCICEX '96 Hi and Lo Resolution Ice Keel Data

The user can "click and drag" with the mouse to select the desired region, or type explicit latitude and longitude bounds into the numeric query screen to retrieve data from the geographic area of interest.

Fast Tactic provides a powerful tool for evaluating environmental conditions that affect cruise and science decisions. Its particular focus is on submarines operating under ice in the Arctic. The ability to examine ice draft data over a track or operating area for thin ice is a particularly useful feature, allowing the submarine crew to quickly locate areas of thin ice where surfacing can be done safely.

SOARED Interface Features

The SOARED graphical user interface (GUI) is designed to facilitate access to the underlying database using simple mouse operations (point, click, and drag). For example, defining a region is quickly and easily accomplished by using the "click and drag" technique. Additionally, various data display options are available by simply clicking a checkbox option. For example, by selecting the PLOTS option, a color-coded X-Y plot is automatically displayed on the screen.

When displaying multiple data parameters at once, each parameter can be removed from and returned to view by simply clicking on a toggle key. Similarly, individual depth profiles or along-track data segments can be highlighted using the mouse: this capability allows one to quickly identify data and associated regions of special interest, such as thin or no ice cover locations.

Summary

Fast Tactic provides the capability for an investigator to collect, store, retrieve, and analyze data while at sea or ashore. The system can be used to complement other science data storage systems, or as a standalone database. Data storage can be either automatic or manual. By storing the data in the Fast Tactic relational database, the investigator can transfer that data more easily into the ADCC or other data storage systems on completion of a cruise. Fast Tactic also allows a quick analysis of available historical data to locate data gaps in either time or space to make cruise plans that can fill those gaps. Manipulation and examination of Fast Tactic displays is simple: selection of parameters for display on a chart or graph is made with the mouse, without typing on the keyboard.

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Use of an International Fleet of Polar Rovers to Perform Long-Range Transects of Polar Seas, Acquiring Key Climate-System Data

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Sea ice is an interesting material when examined as an environmental integrator as has been discussed recently in papers by Fetterer and Untersteiner and Richter-Menge. The annual cycle of ice production represents a cycle of heat flux for the region north of 70°N, of only 20 W/m^2, a very high sensitivity. Investigators monitoring this sea ice thickness using submarine upward-looking sonar find multiyear variation in mean ice thickness to be significant, although there is a vigorous disagreement on the interpretation. Thus, the sea ice thickness is, on the one hand a sensitive integrative indicator of large-scale seasonal fluxes, and on the other hand a signal that involves expensive logistics, and in the end, a variable that is difficult to interpret.

The realistic use of sea ice thickness as a valuable climate indicator requires that the numerical simulation of processes controlling thickness be made more accurate and that the measurement of the thickness distribution, required to support model development on the short term and initiate and validate model results on the longer term, be made sufficiently accurate and extensive. Clearly, determination of sea ice thickness distribution from space is highly desirable; however, sea ice, including its snowcover, is spatially and electromagnetically complex such that the development of a spaceborne approach is a significant challenge; it may well be a decade or more before such measurements are made. For the intervening period, and for validation of the instruments designed for space deployment, a surface rover-based strategy is capable and cost effective.

The NASA planetary program relies on rover-based science, and NASA has an aggressive program in the development of scientific and operational autonomy to advance in situ explorations. These rover designs vary widely, but some are clearly of use in Earth science, and the Inflatable Rover is, in particular, an excellent candidate for long-range, solar-powered, autonomous transects of the Arctic Ocean (or other ice-covered sea), and there are a number of ice-thickness determination instruments in various stages of development for measuring sea ice thickness distribution with accuracy comparable to the submarine results.

IPY4 is gaining momentum around the world, and a polar rover program constitutes an excellent activity in that program. Ice covered seas are a mix of international and national (EEZ) waters, and the climatological processes of interest that act on them are clearly global; this science is inherently international. The technologies required for an autonomous scientific transect of the Arctic Ocean or the Southern Ocean are similarly of wide interest. Participation in the polar rover fleet can be at a variety of levels; a nation or agency can supply an entire instrumented rover or a subsystem such as an instrument. A workable fleet would be two-to-four vehicles, each addressing a separate aspect of the sea ice-atmosphere-ocean system (e.g. ice thickness, radiation balance, microwave properties, snow character, weather, air chemistry) and collaborating where appropriate.

We will discuss rover design issues, progress in polar rover deployments to date, instrumentation possibilities, and an approach to forming an international team of ice and climate rovers for an opportunity such as IPY4.

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Metadata, Long-Term Archiving and ARCSS Data Coordination Center Data-Management Services

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Metadata describe the "who, what, where, when, why, and how" of data sets and are crucial to an investigator looking for suitable data to answer specific research questions.

Metadata comprise information about the data, and preserve the usefulness of data over time. Numerous examples demonstrate that data can become useless if relevant metadata, or information about data, are missing (National Research Council 1995). The Arctic System Science (ARCSS) Data Coordination Center's (ADCC) emphasis on metadata is an important factor that sets it apart from archives without a long-term perspective. The ADCC collects, reviews, packages, and presents metadata with every data set. Because the research community can use data for purposes that may differ from the original reason the data were collected, the long-term archive of ARCSS data has a much broader audience than just ARCSS investigators.

The ADCC is the central, long-term archive for data collected by the National Science Foundation's ARCSS Program. The ADCC is located at the National Snow and Ice Data Center, which is an information and referral center supporting cryospheric research. The primary goal of the ADCC is to collect ARCSS data and to provide for its long-term preservation and distribution, ensuring that the data will be usable by both current global change researchers and future generations.

The ARCSS Program, by definition, is focused on the science of environmental systems, and is defined geographically, rather than by discipline. Because successful system science requires the sharing of data, these programmatic characteristics require strong dedication to the preservation and distribution of ARCSS data (Codispoti et al. 2001). The ADCC maintains high standards for data management to meet the needs of the current users of the ARCSS data collection, as well as to ensure the long-term viability of the data, by collecting thorough and comprehensive data documentation for all data sets, including metadata.

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PARCS Data Management in Support of Reconstructions of Arctic Environmental Change

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Central to the PARCS program is an understanding of arctic environmental change over time periods longer than the historical record (PARCS, 1999, Imperative One). For PARCS, the Data Management Officer (DMO) plays a key role in this process by helping to integrate individual efforts (both modern and proxy) in order to generate a spatial and temporal picture of environmental change. The DMO supports these efforts and adds value to these results by preserving them, and providing supplemental information via a public data archive.

As PARCS research extends beyond the historical record we must be highly critical of the fidelity and chronology of our primary data. As an example, when we constructed the *Paleoenvironmental Atlas of Beringia* (www.ncdc.noaa.gov/paleo/parcs/atlas) the DMO worked closely with the community doing quality control to create the primary data archive thereby ensuring a solid foundation for synthetic efforts based on these data.

PARCS DMOs must have a base-level understanding of the primary data so they can facilitate its calibration. When dealing with multiple proxy indicators such as in the current PARCS project to reconstruct the Holocene Thermal Maximum, multiple calibrations that reconstruct compatible aspects of the environment are needed. In some cases these calibrations are done by the DMO, in other cases, the DMO assembles them into the data archive.

Although individual proxy reconstructions provide a great deal of information about the arctic environment, when these reconstructions are viewed as a network of sites in time and space, their value increases. The third focus of the DMO is to help PARCS assemble this network. For the current PARCS work with arctic temperature (see Hughen et al. talk, this meeting), the DMO worked closely with the working group to gather data from the community and build the site network.

The final focus of the DMO is to present the reconstructions. PARCS' philosophy is to present the reconstructions in concert with the primary data and the individual site interpretations. Additionally, we describe the methods used during interpretation and analysis. The result is an integrated resource where one can view our science, and also access data of interest. It is in this area that our collaboration with the World Data Center – A (WDC-A) for Paleoclimatology in Boulder, Colorado, USA, has value. A current development project between PARCS and the WDC-A (due out in July 2004) will support this kind of data resource.

Reference

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The Hydrologic Cycle and Its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study

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The hydrologic cycle and the environment of the Arctic are changing rapidly. There is mounting evidence that the productivity of terrestrial ecosystems, the balance of energy, water, and carbon, and the dynamics of the Arctic Ocean and atmosphere are all likely to be changing due to a variety of environmental factors including greenhouse warming. Water figures prominently in such changes. The stature and relative abundance of plants may be changing, producing new patterns of feedback to regional and global energy, water, and carbon balances. Increases in freshwater transport to the Arctic Ocean may at some point reduce the formation of North Atlantic Deep Water, resulting in a cooling in the North Atlantic region and a reduction in global ocean circulation. Because such changes are of potentially enormous global importance, a better understanding of arctic hydrology is critical.

There are several notable gaps in our current level of understanding of arctic hydrological systems. At the same time, rapidly emerging data sets, technologies, and modeling resources provide us with an unprecedented opportunity to move substantially forward.

The Arctic Community-Wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP), funded by NSF/ARCSS, was established to initiate a major effort to improve our current monitoring of water cycle variables, and to foster collaboration with the many relevant U.S. and international arctic research initiatives. The first set of projects, funded under ARCSS through the "Freshwater Initiative," links CHAMP, the Arctic/Sub-arctic Ocean Fluxes (ASOF) Programme, and SEARCH. This poster will provide an update on the establishment of the new Arctic-CHAMP Science Management Office, and an overview of ongoing Freshwater Initiative Projects focusing on the arctic hydrologic cycle.

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USGS High Resolution Digital Elevation Models and Data Fusion Research over Teshekpuk Lake C-2, Alaska

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The National Petroleum Reserve-Alaska (NPR-A) consists of a 23 million-acre reserve on the North Slope that was established in 1923 because of the region's promising petroleum potential. Currently, the Bureau of Land Management (BLM) is responsible for proposed oil and gas leasing. BLM's responsibilities include analysis of environmental impacts of proposed oil well placement. Key to this analysis is accurate high-resolution digital elevation data. Through the USGS Land Remote Sensing Program, the BLM has recently acquired Interferometric Synthetic Aperture Radar (IFSAR) as part of an ongoing collection cycle over the NPR-A area. IFSAR products include Digital Surface Model (DSM) and Digital Terrain Model (DTM) bare-earth elevation data at 5-meter post spacing, and Ortho-Rectified Radar Image (ORRI) magnitude data at 1.25-meter resolution. USGS personnel at the Rocky Mountain Mapping Center in Denver, Colorado, have been working closely with BLM-Alaska scientists to provide experimental IFSAR-based products for use in several analytical studies. For example, USGS researchers used the latest hydrographic modeling tools to model flow in an extremely low-relief area of the NPR-A, and presented the results to BLM as a potential solution in their catastrophe simulation. New data-fusion and three-dimensional perspective products created from combinations of IFSAR, color infrared DOQ, Landsat-7 ETM+ imagery, DLG, and DRG data sources now exist for several sample areas within NPR-A. As of this printing, the USGS and BLM cooperators are evaluating the research results and new products to determine which are most useful to the BLM analyses.

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Arctic Sea Ice and Sea Surface Temperature Observations Using Low-Cost Unpiloted Aerial Vehicles

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Routine observations of polar ocean and atmospheric conditions present a variety of problems for piloted aircraft. Unpiloted Aerial Vehicles (UAVs) can alleviate many of these problems by providing a relatively low-cost platform capable of collecting a range of research-quality measurements while operating with little risk. One such UAV, the Aerosonde, is undergoing development and testing with two mission periods per year since 2000 in the Barrow, Alaska, area, with flights over pack ice, shore-fast ice and open ocean.

Currently, Aerosondes are capable of collecting air temperature, humidity, pressure, wind speed and direction, digital photographs, and skin temperatures over distances as great as 1,000 km from the launch site. These data have been used to map ice conditions, including ice and lead features, melt ponds, and surface temperature; to photograph the Barrow coastline; and to acquire concurrent atmospheric data along transects and vertical profiles over the ice pack. Additional instrumentation in development includes a laser profiler to retrieve ice roughness and draft, a miniaturized synthetic aperture radar for surface mapping, and broadband pyranometers to measure radiative fluxes. Here, we describe capabilities and limitations of the aircraft, and review results pertaining to investigations of sea ice conditions and sea surface temperatures in and near the marginal ice zone in the Beaufort and Chukchi Seas.

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The Cold Land Processes Pathfinder: A Spaceborne Mission Concept for Cyrosphere Studies

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Cold land areas, cold areas of the Earth's land surface where water is frozen either seasonally or permanently, form a major component of Earth's hydrologic system, and interact significantly with the global weather and climate system, the geosphere, and the biosphere. The influence of seasonally and permanently frozen land surfaces extends to engineering in cold regions, trafficability for humans and other animals, and a variety of hazards and costs associated with living in cold lands.

The Cold Land Processes Pathfinder (CLPP) mission concept has been developed by the NASA Terrestrial Hydrology Program's Cold Land Processes Working Group to measure critical components of the terrestrial cryosphere. The concept will utilize synergistic active and passive microwave remote sensing to address broad NASA Earth Science Enterprise objectives in hydrology, water resources, ecology, and atmospheric sciences. The CLPP employs a combination of dual-frequency Synthetic Aperture Radar (C- and Ku-band) and dual-frequency radiometers (18- and 37-GHz). The radar and radiometer sensors share a ~2-m reflector antenna with a near-nadir viewing angle. The SAR measurement resolution is better than 100 m, and the passive radiometer footprint is less than 5 km. The swath width is on the order of 25 km. Thus, the CLPP will provide a nearly ideal combination of multi-frequency microwave measurements, but at fewer locations around the Earth than an operational mission might.

The CLPP measurements will provide, for the first time, a set of microwave measurements with ideal characteristics to measure and characterize snow over land. The CLPP SAR component is based on a heritage of ground studies and the SIR-C/X-SAR experiment, which demonstrated the ability to measure key snow properties using physically based (i.e., first-principle radiative transfer response to snow properties) retrieval algorithms based on dual-frequency SAR. The CLPP radiometer component is based on extensive understanding of passive microwave remote sensing of snow, and a nearly three-decade legacy of snow estimation using SMMR, SSM/I, and now AMSR. The coarse resolution (~30 km) of these passive sensors, and the significant problems created by complex mixed pixels has limited this approach to empirically based retrievals that are typically valid only for relatively simple terrain. By pairing high-frequency SAR with dramatically improved-resolution radiometry, the CLPP will yield a long-awaited breakthrough in global snow measurement. Frequent reliable measurements of snow water equivalent and snow wetness, even within the limited swaths of this pathfinder, will comprise an improvement in snow measurement several orders of magnitude better than provided by existing ground observation networks.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Unified Ecoregions of Alaska: 2001

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The Unified Ecoregions of Alaska map portrays major ecosystems of the state of Alaska and neighboring portions of Canada and Russia. The word "unified" in the title refers to the interdisciplinary, interagency, and international effort to derive this broad-scale ecosystem map. The ecoregions, as portrayed on this data set, are large ecosystems primarily defined by climate and topography, with refinements from vegetation patterns, lithology, and surficial deposits. Ecoregions are tens of millions of acres in size and correspond to the Province level of Bailey's hierarchy (1980, 1995).

A total of thirty-two ecoregion units were mapped, representing the major ecosystems of Alaska. Ecoregions were mapped in their entirety, with some spanning international boundaries to include portions of Canada and Russia. These ecoregions are characterized with written descriptions, tables of environmental variables, and photographs.

Reference

Nowacki, Gregory; Spencer, Page; Fleming, Michael; Brock, Terry; and Jorgenson, Torre. *Ecoregions of Alaska: 2001.* U.S. Geological Survey Open-File Report 02-297 (map)

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Arctic Observing Based on Ice-Tethered Platforms

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In 2003, to address the arctic gap in the ocean observing system, the National Science Foundation funded a project entitled: "An Ice-tethered Instrument for Sustained Observation of the Arctic Ocean" in order to produce an ice-tethered variation of the now operational Moored Vertical Profiler (MVP) instrument developed at WHOI. It is envisioned to deploy a loose array of these expendable Ice-Tethered Profilers (ITPs) to repeatedly sample the upper ocean below the perennial ice pack and telemeter the data back in real time to the lab. Long lifetime and modest cost will permit basin-scale coverage (about 20–30 or more systems) to be maintained through regular seeding of replacement systems as necessary, similar to the surface ice buoys (measuring sea ice drift, sea level atmospheric pressure, and 2-meter air temperature) of the International Arctic Buoy Program (IABP). Operationally, the array will serve as the arctic analogue of the ARGO float program now being initiated for lower latitudes (http://www.argo.ucsd.edu/). Development, prototype construction, and field testing of several ITPs in 2004 and 2005 is underway, with implementation of a full field array of ITPs across the Arctic anticipated in 2006. The ITP array would establish a telecommunications link through the surface ice pack that could also serve as the future backbone for two-way transmissions to buoys, AUVs, and subsurface moorings in the Arctic Ocean.

Ideally, an array of these ice-tethered platforms should serve as a very effective monitoring system of the Arctic Ocean, sea ice, and near-surface atmosphere. In order to facilitate development of this system and to coordinate international efforts in arctic monitoring we propose to hold an international workshop entitled "Arctic Monitoring Based on Ice-Tethered Platforms" at the Woods Hole Oceanographic Institution in June 23-25, 2004. This workshop will be a logical continuation of the Arctic Instrumentation Workshop funded jointly by NSF and WHOI in October 2002 at Monterey Bay Aquarium Research Institute, California. We expect that international experts from Canada, Germany, Great Britain, Norway, Russia, USA, and other countries will brainstorm the idea and will significantly contribute to development and implementation of the full Arctic Ocean monitoring system.

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The Swedish Icebreaker *Oden* as a Research Platform: The Arctic Ocean Experiment 2001

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Many studies indicate that the climate sensitivity of the Arctic is larger than anywhere else on the Earth. Studies with Global Climate Models (GCM) estimate the warming of the Arctic to be ~2–3 time larger than the global average. At the same time, the same GCM models disagree more on the arctic warming than anywhere else on the Earth, ranging from a factor of <1 to a factor of five times the global average. We believe that a large part of this extra arctic uncertainty derives from inadequate descriptions of vital climate processes that are specific to the Arctic. These so-called parameterizations are necessary to describe processes occurring on a spatial and/or temporal scale much smaller that can be explicitly resolved in a GCM. The specific relationships between these processes and the resolved scale atmosphere are always empirical to some degree. The problem is that most of the experimental evidence for such descriptions comes from field experiments in the mid-latitudes and the tropics, and often from land. Due to the very special features of the Arctic Ocean, many such results may be invalid in an arctic setting, and the only remedy to this dilemma is field experiments in the Arctic.

Fieldwork in the central Arctic, however, is much more complicated than at many other locations. Even getting there requires special attention. Much of the work has to be done on ice that is drifting and may break up at any point in time, and the structure of the ice restricts the kind of installations that can be erected. The risk of losing or damaging instrumentation makes one think twice about what is put up on the ice. And even if all this is successful the arctic environment remains quite hostile. It is difficult to move about on the ice and the conditions are quite hostile to modern electronics; during winter, it can become very cold and in summer, everything is very humid. Success thus requires logistics support of an unusual character.

The Arctic Ocean Experiment 2001 (AOE-2001) will be described. This experiment was launched on the Swedish icebreaker *Oden* to take measurements of boundary-layer dynamics, atmospheric chemistry, aerosol chemistry/physics to help understand the processes that govern cloud formation and cloud characteristics in the summer central Arctic. Complementary observations of marine biology were also performed to investigate links between biological activity in the ice and in open leads and the formation of aerosols. Most of the atmospheric chemistry and aerosol measurements and much of the marine biology work was performed in laboratories onboard, either in the permanent laboratory on the foredeck, or in temporary container-based laboratories. Also, some of the meteorological measurements were performed onboard: a wind profiler, a cloud radar, a scanning passive microwave radiometer and radiosoundings and regular weather station data. Other meteorological measurements were too severely disturbed by the *Oden* itself, and had to be deployed in the ice. This was done during a three-week ice drift; two sodar systems, a mast with turbulence flux and wind and temperature profile instruments, tethered soundings, and two remote Integrated Surface Flux Facility stations. This undertaking would not have possible without access to a platform like *Oden* and the logistical support by the Swedish Polar Research Secretariat and by the crew of *Oden*.

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The Barrow Area Information Database - Internet Map Server (BAID-IMS)

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The Barrow Area Information Database - Internet Map Server (BAID-IMS) is a prototype project that has been developed under the emerging Spatial Data Infrastructure (SDI) activities coordinated by the Digital Working Group (DWG) of the Barrow Arctic Science Consortium (BASC). As well as remote sensing products, topographic maps, and current research information, BAID-IMS contains information about historical research conducted in the Barrow area in northern Alaska dating back to the 1940s. This information is used freely and interactively by researchers, land managers, educators, and the local community to access spatial data and information on terrestrial, marine, freshwater, and atmospheric research in the Barrow area. The Barrow area in this application is defined as the region encompassed between the North Slope village of Barrow in the north, to Teshekpuk Lake in the east, to the villages of Atqasuk in the south, and Wainwright in the west.

All information in this application is accompanied by metadata that meets the standards of the Federal Geographic Data Committee (FGDC), and it is hoped that data will be available for downloading at The Arctic System Science (ARCSS) Data Coordination Center (ADCC) at the National Snow and Ice Data Center (NSIDC) located at the University of Colorado in Boulder, USA. BAID-IMS was developed by the Arctic Ecology Laboratory at Michigan State University and Nuna Technologies under contract to BASC, which is supported by the Office of Polar Programs (OPP) at the National Science Foundation.

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CEON: A Terrestrial Circum-Arctic Environmental Observatories Network

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The concept of a terrestrial Circum-arctic Environmental Observatories Network (CEON) was introduced at Arctic Science Summit Week (ASSW) in 2000 at a meeting of the Forum of Arctic Research Operators (FARO: www.faro-arctic.org). CEON is conditioned by the need for increased international integration of research effort and the loss and/or danger of loss of continuous northern high-latitude environmental observations. FARO has endorsed the CEON concept advocating that CEON be developed to promote environmental measurements and dissemination of these to arctic researchers while encompassing and building on the strengths of existing arctic stations and environmental observatory networks. Since 2000, the CEON concept has increasingly received enthusiastic support from a variety of existing networks, disciplinary collaborations, and research stations as well as endorsement from the International Arctic Science Committee (IASC) (www.iasc.no).

Since the formation of a working group at ASSW 2002 to scope and develop the concept of CEON, presentations have been made at meetings of various networks, research collaborations, and polar research boards in Europe, Russia, and the United States in order to make contact and collect feedback from potential CEON stakeholder and user groups. Presentations have focused on the necessity for the CEON initiative to meet and promote the needs of the participating research community, science administrators, policy makers, industry, education, and indigenous communities. In doing so, it has been stressed that CEON should be seen as a network that facilitates and encourages environmental monitoring, which provides linkages between disciplines and existing networks, and connectivity spanning regional to circum-arctic and global scales. Following CEON presentations audiences have been asked to introduce their own bias in the development of CEON by providing feedback to the following question: "What would you do if you had the opportunity to conduct standardized, long-term, integrated measurements across all research stations and networks in the Arctic?" This approach has facilitated the development of CEON based on the experience, needs, and future directions envisaged by an international and broad range of potential CEON stakeholder and user groups.

The CEON initiative should not be seen as duplicating prior or ongoing research effort, but as an international partnership that aims at forming a logistical and research framework within which ongoing and future research can be oriented to cumulatively form and facilitate long-term research endeavors in the Arctic. Based on recent scoping and development activities and the convention of the first planning meeting in October 2003, this presentation recapitulates the enthusiastic support for the initiation of CEON and outlines a conceptual roadmap for its inception. We invite your thoughts and ideas to facilitate the development of the CEON initiative.

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Facilitating Arctic and Geosciences Research with the Former Soviet Union

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The U.S. Civilian Research and Development Foundation (CRDF) for the independent states of the former Soviet Union is a private, nonprofit, grant-making organization created in 1995 by the U.S. government (National Science Foundation).

The CRDF promotes scientific and technical collaboration between the U.S. and the countries of the former Soviet Union (FSU). The foundation's goals are to support scientific cooperation in basic and applied research; advance the transition of former weapons scientists to civilian activities; and to encourage R&D cooperation between U.S. industry and FSU science.

Three CRDF programs provide support to U.S. scientists engaged in collaborative arctic and geosciences-related research in the FSU. First, under a contract with the National Science Foundation, CRDF provides an office and personnel in Moscow to assist Office of Polar Programs (OPP) and Geosciences Directorate (GEO) grantees and collaborators with programmatic activities, including identifying and communicating with individual and institutional partners, navigating government agencies, facilitating travel and visas, and providing on-site office support to visiting U.S. travelers. Second, the CRDF Cooperative Grants Program allows U.S.-FSU collaborators in arctic sciences and geosciences to apply for two-year R&D grants averaging approximately $80,000. Third, the CRDF Grant Assistance Program (GAP) enables U.S. government agencies, universities, and other organizations to utilize CRDF's financial and administrative infrastructure to transfer payments, purchase and deliver equipment and supplies, and carry out other project management services to collaborators in Russia and elsewhere in the FSU.

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Appendix C

SEARCH Open Science Meeting Agenda

Sunday, 26 October 2003

6:30 pm - 9:30 pm
Icebreaker Reception and Registration
(International Promenade)

Day 1 - Monday, 27 October 2003

Theme: Changes and Impacts
(Plenary Sessions in Bay Auditorium)

7:30 am - 8:30 am
Registration
(Entry Lobby)

8:00 am
Continental breakfast
(Kiosks)

8:30 am
Welcome and Introductions
James Overland
Session Chair; Chair, Open Science Meeting Organizing Committee, National Oceanic and Atmospheric Administration

8:50 am
Findings of the Recent Arctic Climate Impact Assessment
Robert Corell
Senior Fellow, Harvard University and American Meteorological Society

9:20 am
Regional View: Perceptions and Concerns About Change
Caleb Pungowiyi
President, Robert Aqqaluk Newlin, Sr. Memorial Trust

9:50 am
Inuit and Climate Change: Influencing the Global Agenda
Sheila Watt-Cloutier
Chair, Inuit Circumpolar Conference

10:20 am
Break

10:50 am
Introduction to Parallel Science Sessions
Craig Nicolson
University of Massachusetts

11:10 am
Plenary Discussion

11:30 am
Lunch
(Harbor Dining Room)

1:00 pm
Parallel Science Sessions: Changes and Impacts
SEARCH has been motivated by observations, in recent years, of a complex of seemingly interrelated, decadal scale, pan-arctic changes. These have been seen on land, in the sea, and in the atmosphere, and appear connected to changes at lower latitudes. Each parallel session will begin with a set of contributed papers and then will open for discussion aimed toward updating our understanding of previously observed changes, exploring new changes, and evaluating their consequences.

I. Changes on Land

(Bay Auditorium) *See detailed agenda on page 303.*
Topics such as, but not limited to, snow cover; permafrost; glaciers; hydrology; species composition, distribution, and abundance; subsistence harvesting; carbon (CO_2 and methane)
Co-chairs: Matthew Sturm, Cold Regions Research and Engineering Laboratory
Bruce Forbes, University of Lapland

II. Changes in the Sea

(Sound Room) *See detailed agenda on page 308.*
Topics such as, but not limited to, salinity, temperature, currents, nutrients, sea ice, marine ecosystems (including people, marine mammals, and fisheries)
Co-chairs: George Hunt, University of California Irvine
Motoyoshi Ikeda, Hokkaido University

III. Changes in the Atmosphere

(Cove Room) *See detailed agenda on page 313.*
Topics such as, but not limited to, atmospheric pressure and circulation, temperature, cloudiness, precipitation, and evaporation
Co-chairs: Hans von Storch, GKSS Research Centre
Richard Moritz, University of Washington

IV. Coastal Processes

(Marina Room) *See detailed agenda on page 316.*
Topics such as, but not limited to, fate and transport of materials, erosion, effects on human communities
Co-chairs: Volker Rachold, Alfred Wegener Institute
Steven Solomon, Natural Resources Canada

4:30 pm
Poster Session/Reception with cash bar
(International Promenade)

6:30 pm
Buffet Dinner and Sea Level Rise Beach Party
(Odyssey Maritime Discovery Center)

Day 2 - Tuesday, 28 October 2003

Theme: Feedbacks
(Plenary Sessions in Bay Auditorium)

8:00 am
Continental Breakfast
(Kiosks)

8:30 am
SEARCH Vision and Core Hypotheses
James Morison
Session Chair; Chair, SEARCH Science Steering Committee, University of Washington

9:00 am
The Nature, Measurement, and Modeling of Feedbacks
Judith Curry
Georgia Institute of Technology

9:30 am
Arctic Climate Simulations by Coupled Models
Annette Rinke
Alfred Wegener Institute for Polar and Marine Research

9:50 am
Terrestrial Feedbacks: Vegetation, Carbon, and Heat
F. Stuart Chapin
University of Alaska Fairbanks

10:10 am
Break

10:40 am
The Freshwater Cycle and its Role in the Pan-Arctic System
Charles Vörösmarty
University of New Hampshire

11:00 am

Sea Ice: Two Perspectives
Was Sea Ice Quite Thin in the 1990s? Yes
D. Andrew Rothrock
University of Washington

Inter-Annual Variability in Arctic Sea Ice Thickness from Space
Seymour Laxon
University College London

11:40 am

Human-Environment Relations: Responding to the Challenges and Opportunities of Arctic Environmental Change
Mark Nuttall
University of Alberta

12:00 pm

Lunch
(Harbor Dining Room)

1:30 pm

Parallel Science Sessions: Feedbacks
An important working hypothesis of SEARCH is that the complex of pan-arctic changes is driven by a change in the atmospheric circulation of the Northern Hemisphere. To put this in perspective, it is also hypothesized that feedbacks within the arctic system are important in the complex of change, and that some of these feedbacks, along with other linkages to lower latitudes, are important to changes on a global scale. Each parallel session will begin with a set of contributed papers and then will open for discussion of feedbacks and linkages such as, but not limited to, ice-albedo feedback, vegetation-carbon feedback, effect of the freshwater cycle on global thermohaline circulation, and the nonlinear combined effects of environmental change and human activity on the ecosystem.

I. Social Feedbacks

(Marina Room) *See detailed agenda on page 319.*
Co-chairs: Stewart Cohen, University of British Columbia and Environment Canada
Matthew Berman, University of Alaska Anchorage

II. Biological Feedbacks

(Sound Room) *See detailed agenda on page 323.*
Co-chairs: Sue Moore, National Oceanic and Atmospheric Administration
Joshua Schimel, University of California Santa Barbara

III. Physical Feedbacks

(Bay Auditorium) *See detailed agenda on page 326.*
Co-chairs: Michael Steele, University of Washington
Stephen Vavrus, University of Wisconsin

IV. Drivers and Causes

This session relates to Day 3 plenary
(Cove Room) *See detailed agenda on page 329.*
Co-chairs: James Overland, National Oceanic and Atmospheric Administration
Mark Serreze, University of Colorado

4:30 pm

Break

5:00 pm

Panel Discussion: Connections and Key Scientific Issues
(Bay Auditorium)
Moderator: *Ron Clarke, Marine Conservation Alliance*
Panelists: *Mark Dyurgerov, University of Colorado*
Jennifer Francis, Rutgers University
Jack Kruse, University of Massachusetts
Glen MacDonald, University of California Los Angeles
Peter Schlosser, Columbia University
Gaius Shaver, Marine Biological Laboratory

6:30 pm

Poster Session/Reception
with hors d'oeuvres and cash bar
(International Promenade)

8:00 pm

Bering Ecosystem Study (BEST) Open Meeting
(Sound Room)
George Hunt, Chair

Day 3 - Wednesday, 29 October 2003

Morning Theme: Drivers/Causes
(Plenary Sessions in Bay Auditorium)

8:00 am

Continental breakfast
(Kiosks)

8:30 am

Drivers and Causes of Arctic Environmental Change
Mark Serreze
Session Chair, University of Colorado

8:50 am
Natural and Anthropogenic Drivers of Arctic Climate Change
Gavin Schmidt
NASA Goddard Institute for Space Studies

9:20 am
Interannual Variations of Polar Climate: Relationship to Annual Modes
Murry Salby
University of Colorado

9:50 am
Break

10:20 am
Spatial and Temporal Modes of Arctic Climate Variability Over the Past 600 Years
Konrad Hughen
Woods Hole Oceanographic Institution

10:50 am
The Early 20th Century Warming in the Arctic: A Possible Mechanism
Lennart Bengtsson
Max Planck Institute for Meteorology

11:20 am
Arctic System Synthesis: Is the Arctic Headed Toward a New State?
Jonathan Overpeck
University of Arizona

11:50 am
Student Presentation

12:15 pm
Lunch
(Harbor Dining Room)

Afternoon Theme: Understanding and Predicting Change
(Bay Auditorium)

1:45 pm
How Does SEARCH Fit into the Larger Scheme of U.S. Climate Change Science?
James Mahoney
Director, U.S. Climate Change Science Program
National Oceanic and Atmospheric Administration

2:15 pm
How Do the Arctic and Sub-arctic Processes Interconnect? What Have We Learned?
Robert Dickson
The Centre for Environment, Fisheries, and Aquaculture Science

3:05 pm
Break

3:30 pm
Panel Discussion: Understanding and Predicting Change in the Arctic System
Moderator: *Andrew Revkin, New York Times*
Panelists: *Lawson Brigham, U.S. Arctic Research Commission*
F. Stuart Chapin, University of Alaska Fairbanks
Robert Dickson, The Centre for Environment, Fisheries and Aquaculture Science
Jonathon Overpeck, Institute for the Study of Planet Earth, University of Arizona
Elaine Abraham, Alaska Native Science Commission

5:10 pm
SEARCH Implementation: What is Being Done and Where Are the Gaps?
James Morison
Chair, SEARCH Science Steering Committee
University of Washington

5:30 pm
Adjournment

Day 4 - Thursday, 30 October 2003

9:00 am - 12:00 pm:
SEARCH International Implementation Forum
(International Promenade)
An open forum to provide the international arctic research community an opportunity to exchange ideas on participation in SEARCH implementation.

Monday, 27 October 2003

Parallel Science Session—Changes on Land

(Bay Auditorium)

Topics such as, but not limited to, snow cover; permafrost; glaciers; hydrology; species composition, distribution, and abundance; subsistence harvesting; and carbon (CO_2 and methane).

Co-chairs: Matthew Sturm, Cold Regions Research and Engineering Laboratory
Bruce Forbes, University of Lapland

1:00 pm
Terrestrial Changes in Polar Regions, Evidence, Attribution, and Implications
Larry D. Hinzman

1:15 pm
GTN-P Monitoring Network: Detection of a 3 K Permafrost Warming In Northern Alaska During the 1990s
Gary D. Clow, Frank E. Urban

1:30 pm
Effects of Climate Change on Tundra Ecosystems
Greg Henry

1:45 pm
The Contribution of Alaska's Glaciers to Global Sea Level Rise
Keith Echelmeyer, William Harrison, Craig Lingle, Martin Truffer (Presenting Author), Anthony Arendt, Virginia Valentine, Sandy Zirnheld

2:00 pm
Hydrological Changes in NW Canada
Philip Marsh

2:15 pm
Arctic Change: Humans as Passengers and Drivers
Bruce Forbes

2:30 pm
Break

2:45 pm
Historical Changes in Seasonal Freeze and Thaw Depths in Russia
Oliver W. Frauenfeld, Tingjun Zhang, Roger G. Barry, David Gilichinsky

2:50 pm
Degradation of Ice Wedges in Northern Alaska in Response to Recent Warmer Temperatures
Torre Jorgenson, Erik Pullman, Yuri Shur (Presenting Author)

2:55 pm
Modeling Evidence for Recent Warming of the Arctic Soil Thermal Regime as Derived with a Finite-Difference Heat-Conduction Model
Christoph Oelke, Tingjun Zhang, Mark C. Serreze

3:00 pm
Measured Climate-Induced Volume Changes of Three Glaciers, and Current Glacier-Climate Response Prediction
Dennis C. Trabant, Rod S. March, Leif H. Cox, Will D. Harrison, Edward G. Josberger

3:05 pm
Pan-Arctic Observations of Inter-annual Snowmelt Change and Application to Flood Forecast
Son V. Nghiem, Gregory Neumann, Matthew Sturm, Donald K. Perovich

3:10 pm
Potential Factors Contributing to Long-Term Increases in Discharge from Large Eurasian Drainage Basins: A Preliminary Analysis
Charles J. Vörösmarty, Richard Lammers, Mark Fahnestock, Steve Frolking, Michael Rawlins, Alexander I. Shiklomanov, Mark Serreze, Richard Armstrong, Christoph Oelke, Tingjun Zhang, Bruce J. Peterson, Robert M. Holmes, James W. McClelland

3:15 pm
Streamflow Changes over the Large Siberian Watersheds: Natural Variation vs. Human Impact
Daqing Yang, Douglas L. Kane, Baisheng Ye

3:20 pm
Permafrost Thawing and Hydrologic Response Over the Russian Arctic Drainage Basin
Tingjun Zhang, Roger G. Barry, Mark Serreze, Daqing Yang, Andrew J. Etringer, David Gilichinsky, Oliver Frauenfeld, Hengchun Ye, Christoph Oelke, Feng Ling, Sveta Chudinova

3:25 pm
Changes in the Environment and Ecology at Toolik Lake, Alaska
John E. Hobbie

3:30 pm
Eighteen Years of Vegetation Monitoring in the Arctic National Wildlife Refuge, Alaska
Janet C. Jorgenson

3:35 pm
Detecting Arctic Climate Change Using Köppen Climate Classification
Muyin Wang, James E. Overland

3:40 pm
The Response of the Alaskan Boreal Forest to a Warming Climate
Valerie A. Barber, Glenn P. Juday, Martin Wilmking

3:45 pm
Atmosphere-Ocean Teleconnections and Alaskan Forest Fires
Paul A. Duffy, John E. Walsh, Daniel H. Mann, Scott Rupp

3:50 pm
Global Boreal Forest Responses to Climate Warming
Glenn P. Juday, Valerie A. Barber, Eugene A. Vaganov, Edward Berg

3:55 pm
Discussion

4:30 pm
Adjourn to Poster Session

Monday, 27 October 2003

Posters—Changes on Land

Simulated Water and Energy Fluxes of the Pan-Arctic Land Region
Jennifer C. Adam, Fengge Su, Dennis P. Lettenmaier

Late-Holocene Lake-Level Variation in West Greenland
Frank A. Aebly, Sherilyn C. Fritz

Rapid Wastage of Alaska Glaciers: The Search for Climatic Causes
Anthony Arendt, Keith Echelmeyer, William Harrison, Craig Lingle, Virginia Valentine, Sandra Zirnheld

The Response of the Alaskan Boreal Forest to a Warming Climate
Valerie A. Barber, Glenn P. Juday, Martin Wilmking

Changes in River Runoff over the East-Siberian Sea Basin
Sveta Berezovskaya

The Development of Long-term and Spatially Representative Permafrost Databases
Jerry Brown, Vladimir Romanovsky, Frederick Nelson, Kenneth Hinkel, Gary Clow, Roger Barry, Sharon Smith

The Chemical Composition of Snow Across Northwestern Alaska and the Potential Ramifications of a Warming Arctic
Thomas A. Douglas, Matthew Sturm

Atmosphere-Ocean Teleconnections and Alaskan Forest Fires
Paul A. Duffy, John E. Walsh, Daniel H. Mann, Scott Rupp

International Polar Year 2007–2008
Chris Elfring, Sheldon Drobot

Observation of Snowmelt Progression in Northern Alaska with Spaceborne Active Microwave
Richard R. Forster, Lynne Baumgras

Historical Changes in Seasonal Freeze and Thaw Depths in Russia
Oliver W. Frauenfeld, Tingjun Zhang, Roger G. Barry, David Gilichinsky

Direct Observation of Winter Sublimation and Its Effects on the Arctic Climate
Yoshinobu Harazono, Walter C. Oechel, Akira Miyata

Lightweight Shallow Ice Coring and Borehole Logging Can Provide Decadal- to Millenial-Scale Indicators of Climate Change Around the Arctic Basin
Robert L. Hawley, Edwin D. Waddington, Joseph R. McConnell, Dale P. Winebrenner

In Search of the Younger Dryas at Elikchan Lake, Northeast Siberia
Heather D. Heuser, Patricia M. Anderson, Linda B. Brubaker, Ron S. Sletten, Thomas A. Brown

Consideration of Permafrost Thaw as a Significant Contributor to Increasing Eurasian Arctic River Discharge
Robert M. Holmes, James W. McClelland, Bruce J. Peterson

Carbon Storage and the Role of Cryoturbation in the High Arctic: Thule, Greenland
Jennifer L. Horwath, Ronald S. Sletten

Global Boreal Forest Responses to Climate Warming
Glenn P. Juday, Valerie A. Barber, Eugene A. Vaganov, Edward Berg

Extreme Runoff Events in Arctic Alaska
Douglas L. Kane, Larry D. Hinzman, James P. McNamara, Daqing Yang

Arctic Ungulates in a Changing Climate
David R. Klein

R-ArcticNet v3.0 - A New and Improved River Discharge Database to Meet the Needs of High-Latitude Geoscientific Research
Richard B. Lammers, Alexander Shiklomanov, Charles Vörösmarty

The Spatio-Temporal Pattern of Peatland Development in the Western Siberian Lowlands and the Potential Impact of Northern Peatlands on the Global Carbon Cycle
Glen M. MacDonald, Lawerence Smith, Konstantine Kremenetski, Yongwei Sheng, David Beilman, Karen Frey, Andrei Velichko

High-Resolution Imagery and Terrain Model for Collaborative Research of Environmental Change at Barrow, Alaska
William F. Manley, Leanne R. Lestak, Craig E. Tweedie, James A. Maslanik

Trends and Variability in Pan-Arctic Springtime Thaw Monitored with Spaceborne Microwave Remote Sensing
Kyle C. McDonald, John S. Kimball, Eni Njoku, Steven W. Running

Warm Times/Cold Times in Iceland: Are the Last 500 Years Representative of Holocene Climate Variability?
Gifford H. Miller, Aslaug Geirsdottir, Jessica Black

Pan-Arctic Observations of Inter-annual Snowmelt Change and Application to Flood Forecast
Son V. Nghiem, Gregory Neumann, Matthew Sturm, Donald K. Perovich

The SEARCH for New DEMs in the Arctic
Matt Nolan

Modeling Evidence for Recent Warming of the Arctic Soil Thermal Regime as Derived with a Finite-Difference Heat-Conduction Model
Christoph Oelke, Tingjun Zhang, Mark C. Serreze

Rain-On-Snow Events Impact Soil Temperatures and Affect Ungulate Survival
Jaakko Putkonen

Linking *Cassiope tetragona* Growth and Reproduction to High-Arctic Cimate and the Arctic Oscillation
Shelly A. Rayback, Greg H. Henry

Spatial Variability of the Active-Layer Thickness: Observations, Analysis, and Modeling
Nikolay I. Shiklomanov, Frederick E. Nelson

Toward Assessment of the Role of Physical/Chemical Processes in Soil Carbon Cycling in the High Arctic: Thule, Greenland
Ronald S. Sletten, Birgit Hagedorn, Jennifer L. Horwath, Bernard Hallet

In Situ Warming Chambers Stimulate Early-Season Production of *Eriophorum Vaginatum* Leaves and Roots
Patrick Sullivan, Jeffrey Welker

Photography-Based Measurements of the Expansion of Shrubs in Northern Alaska
Kenneth D. Tape, Charles Racine, Matthew Sturm

Measured Climate-Induced Volume Changes of Three Glaciers and Current Glacier-Climate Response Prediction
Dennis C. Trabant, Rod S. March, Leif H. Cox, Will D. Harrison, Edward G. Josberger

Biocomplexity of Frost Boil Ecosystems: Models for Analyzing Self-Organization Across the Arctic Bioclimate Gradient
Donald (Skip) Walker

The Circumpolar Arctic Vegetation Map: A Tool for Analysis of Change in the Arctic
Donald (Skip) Walker, Martha Raynolds, Hilmar Maier

Detecting Arctic Climate Change Using Köppen Climate Classification
Muyin Wang, James E. Overland

Coupling of Carbon and Water in High-Arctic Ecosystems
Jeffrey M. Welker, Ronald Sletten, Bernard Hallet, Josh Schimel, Birgit Hagadorn, Heidi Steltzer, Paddy Sullivan, Jennifer Horwath

Streamflow Changes over the Large Siberian Watersheds: Natural Variation vs. Human Impact
Daqing Yang, Douglas L. Kane, Baisheng Ye

Groundwater Discharge and Periglacial Processes in the Foothills of the Brooks Range, North Slope, Alaska
Kenji Yoshikawa, Larry Hinzman, Douglas Kane

Monday, 27 October 2003

Parallel Science Session—Changes in the Sea

(Sound Room)

Topics such as, but not limited to, salinity, temperature, currents, nutrients, sea ice, marine ecosystems (including people, marine mammals, and fisheries).

Co-chairs: George Hunt, University of California Irvine
Motoyoshi Ikeda, Hokkaido University

1:00 pm
Biological Implications of Arctic Change
Jacqueline M. Grebmeier

1:15 pm
Toward the Next Generation of 3-D Marine Ecosystem Models
Yasuhiro Yamanaka, Taketo Hashioka, Maki N. Aita, Michio J. Kishi

1:30 pm
Polar Marine Mammal Habitat Use May Reflect Climate Change
John L. Bengtson

1:45 pm
The Impact of Climate Patterns on the Bering Sea Ecosystem
Phyllis J. Stabeno, Nicholas A. Bond, George L. Hunt, Carol Ladd, C. W. Mordy

2:00 pm
Distribution, Growth, and Reproduction of Zooplankton in the Northern Barents Sea in Spring: Consequences for Global Change Scenarios
Hans-Jürgen Hirche, Ksenia Kosobokova

2:15
Break

2:30 pm
Climate Impact on the Barents Sea Ecosystem
Harald Loeng, Geir Ottersen

2:45 pm
Spatial and Temporal Variability of Oceanic Heat Flux in the Arctic
Richard A. Krishfield

3:00 pm
Variability in the Arctic Ocean: 1948–1993
Knut Aagaard, James H. Swift, Leonid Timokhov, Yvgeny G. Nikiforov

3:15 pm
Sea Level Change in the Russian Sector of the Arctic Ocean
Andrey Proshutinsky

3:30 pm
Variability of Ice and Ocean Fluxes in the Arctic/Sub-Arctic Domain
Michael J. Karcher, Rüdiger Gerdes, Frank Kauker, Cornelia Koeberle, Ursula Schauer

3:45 pm
Abrupt Change in Deep Water Formation in the Greenland Sea: Results from Hydrographic and Tracer Time Series
Peter Schlosser, Johannes Karstensen, Douglas Wallace, John Bullister, Johan Blindheim

4:00 pm
Discussion

4:30 pm
Adjourn to Poster Session

Monday, 27 October 2003

Posters—Changes in the Sea

Transport and Exchange Across the Fram Strait in 1997–2003: Preliminary Results from the Mooring Arrays
Agnieszka Beszczynska-Moeller, Eberhard Fahrbach, Gerd Rohardt, Ursula Schauer

Using Airborne Remote Sensing, Coupled with Satellite and Shipboard Data, to Map Changes in Coupled Physical and Biological Processes in the Ocean
Evelyn D. Brown, Martin A. Montes Hugo, James M. Churnside, Richard L. Collins

Airborne Thermal Remote Sensing Surveys of Pacific Walrus (*Odobenus rosmarus divergens*) in the Bering Sea
Douglas M. Burn, Marc A. Webber

North Atlantic Oscillation-Driven Changes to Wave Climate in the Northeast Atlantic, and Their Implications for Ferry Services to the Western Isles of Scotland
John Coll, David K. Woolf, Stuart W. Gibb, Peter G. Challenor, Michael Tsimplis

Changes in Sea Ice Microbial Community Composition During an Arctic Winter
Eric Collins, Jody Deming

Progress Towards Understanding Shelf-basin Interactions: Seasonal Variability in the Oxygen Isotope Composition of Arctic Waters in Conjunction with Other Tracers
Lee W. Cooper, Ron Benner, Louis A. Codispoti, Vincent Kelly, James McClelland, Bruce J. Peterson, Robert Holmes, Jacqueline M. Grebmeier

Change in Freshwater Inflow from Glaciers and Rivers to the Arctic Ocean
Mark B. Dyurgerov, Yelena L. Pichugina

Hydrochemical Findings from the North Pole Environmental Observatory Program
Kelly K. Falkner

Highlights of the HLY031 Expedition Hydrographic Program
Kelly K. Falkner, Humfrey Melling, Robie Macdonald, Andreas Muenchow

Recent Arctic Ice Extent Minima Observed with the Sea Ice Index
Florence Fetterer, Ken Knowles, Julienne Stroeve, Mark Serreze, Jim Maslanik, Ted Scambos, Christoph Oelke

An Energy-Conserving Moored Oceanographic Profiler for Marginal Ice Zone Regions, ICYCLER
George Fowler, Simon J. Prinsenberg

Seasonal, Inter-annual and Decadal Variability of the Arctic's Perennial Sea Ice
Jean-Claude Gascard

Achievements and a Potential Role of Underwater Acoustics in Studying Large-Scale Changes in the Arctic Ocean
Alexander N. Gavrilov, Peter N. Mikhalevsky, Valerii V. Goncharov, Yuri A. Chepurin

From the Shoreline Across the Arctic Shelves: Biological Properties of Sea Ice Ecosystems
Rolf R. Gradinger, Bodil A. Bluhm

Overview of the Western Arctic Shelf-Basin Interactions (SBI) Project
Jackie M. Grebmeier

Reconstructing Marine Resource Usage and Trophic Dynamics at Mink Island Site (XMK-030)
Amy C. Hirons, Maribeth S. Murray, Jeanne M. Schaaf

Sea Ice Thickness Measurements by a Low-Frequency Wideband Penetrating Radar
Benjamin Holt, Prasad Gogineni, Vijay Ramasami, Pannir Kanagaratnam, Andy Mahoney, Kyle McDonald

A New Look at Arctic Polynyas with Multi- Sensor Satellite Data
Benjamin Holt, Seelye Martin, Ron Kwok, Robert Drucker

Bering Ecosystem Study Program (BEST)
George L. Hunt, Phyllis Stabeno, Jeffery Napp, Raymond Sambrotto

Sub-Diurnal Mesoscale Sea Ice Deformation in the Spring Beaufort Sea Seasonal Ice Zone and Its Influence on the Sea Ice Mass Balance
Jennifer K. Hutchings, Joe Lovick, William D. Hibler

Spatial Variations in Sea Ice Habitats, Marine Mammals, and Food Resources
Chadwick V. Jay

Distribution of the Convective Lower Halocline Water in the Eastern Arctic Ocean
Takashi Kikuchi, Koji Shimada, Kiyoshi Hatakeyama, James H. Morison

Annual Cycles of Multiyear Sea Ice Coverage of the Arctic Ocean: 1999–2003
Ron Kwok

Sub-daily Sea Ice Motion and Deformation from RADARSAT Observations
Ron Kwok

Narwhal Pack-ice Habitat: Increasing Threats?
Kristin L. Laidre, Mads Peter Heide-Joergensen

Vertical Export of Particulate Organic Carbon and Calibration of Sediment Traps Using 234Th in the Barents Sea
Catherine Lalande, Jackie M. Grebmeier, Paul Wassmann, S. B. Moran, Lee W. Cooper

Arctic Sea Ice Variations and Relations to Atmospheric Forcing
Jouko Launiainen, Pekka Alenius, Milla Johansson, Nick Rayner, Petteri Uotila

Modelling Ice Algae Growth and Decay in Seasonally Ice-covered Regions of the Arctic Ocean
Diane Lavoie, Ken Denman

Variability of Sea Ice Thickness and Thickness Changes in the Arctic
Ron Lindsay, Jinlun Zhang

Palynological Evidence for Holocene Climate Variability in the Laptev and Kara Seas (Eurasian Arctic)
Jens Matthiessen, Martina Kunz-Pirrung, Matthias Kraus

Observations from the Canada Basin: 1997–2003
Fiona A. McLaughlin, Eddy C. Carmack, Koji Shimada, Motoyo Itoh, Shigeto Nishino

Changes in Arctic Productivity: Is it Ice?
Peter McRoy, Rolf Gradinger, Alan Springer, Bodil Bluhm, Sara Iverson, Suzanne Budge

Late Holocene Environmental Change in SW Greenland and the Fate of the Norse
Naja Mikkelsen, Antoon Kuijpers

Submarine Melting at Temperate Tidewater Glacier Termini: How Significant Is It?
Roman J. Motyka, Martin Truffer

Basin-Scale Arctic Ocean Transient Tracer Data Sets
Robert Newton, Peter Schlosser, Bill Smethie, Brenda Ekwurzel, Samar Khatiwala

Arctic Changes Observed with Scatterometer Products
Son V. Nghiem, Donald K. Perovich, David G. Barber

Sunlight Removal of CDOM from the Mackenzie River: Implications for Ocean Color in the Beaufort Sea
Christopher Osburn, Warwick F. Vincent

Changes in the Overflow Through the Faroe Bank Channel
Svein Østerhus

Sea Ice Velocity in the Fram Strait Monitored by Moored Instruments
Svein Østerhus, Karolina Widell, Tor Gammelsrød

Sea Ice Mass Balance Measurements: Insights and Inferences
Don Perovich, Jacqueline Richter-Menge, Ignatius Rigor, James Overland, Bruce Elder, Thomas Grenfell, Hajo Eicken

Quantitative Importance of Macrofauna: A Test of Sieve Mesh Size Biases on Sampling in a High Benthic Biomass Area
Rebecca Pirtle-Levy, Jackie M. Grebmeier, Lee W. Cooper

Inter-annual Variability of the Distribution of the Types of Halocline Within the Central Arctic Basin
Sergey V. Pisarev, David S. Darbinian

Observing Ocean Fluxes Through Lancaster Sound of the Canadian Arctic Archipelago
Simon J. Prinsenberg

Ice Seals as an Indicator of Change in the Arctic Marine Environment
Lori T. Quakenbush, Gay Sheffield

Arctic Warming Through the Fram Strait in the Late 1990s
Ursula Schauer, Michael Karcher, Svein Osterhus

Recent Sedimentation Processes and Transport Pathways of Terrigenous Material in the Kara Sea and the Adjacent Arctic Ocean
Frank Schoster, Masha V. Bourtman, Klaus Dittmers, Mikhail A. Levitan, Tatjana Steinke, Ruediger Stein

Multi-Disciplinary Investigations at an Arctic Deep-Sea Long-Term Station
Thomas Soltwedel, Karen von Juterzenka, Michael Klages, Jens Matthiessen, Eva-Maria Noethig, Eberhard Sauter, Ingo Schewe

The Circulation of Summer Pacific Water in the Arctic Ocean
Michael Steele, James Morison, Wendy Ermold, Ignatius Rigor, Mark Ortmeyer, Koji Shimada

Short-term Variability of River Discharge in the Kara Sea (Arctic Ocean) and Environmental Significance
Ruediger Stein, Klaus Dittmers, Frank Niessen, Jens Matthiessen

Effects of Variability in Hydrographic Structures on Biological Activity in Bering Strait Over Four Years, 2000–2003
Terry E. Whitledge, Sang H. Lee

Arctic Oscillation and Inter-annual Variations of Heat Flux Associated with Oceanic Upwelling
Jiayan Yang

Hydrographic Changes in Baffin Bay, 1916–1999
Melissa Zweng

Monday, 27 October 2003

Parallel Science Session—Changes in the Atmosphere

(Cove Room)

Topics such as, but not limited to, atmospheric pressure and circulation; temperature; cloudiness; precipitation and evaporation.

Co-chairs: Hans von Storch, GKSS Research Centre
Richard Moritz, University of Washington

1:00 pm
Pan-Arctic Change Over the Instrumental Record
James E. Overland, Muyin Wang, Michael C. Spillane

1:20 pm
New Satellite Observations of Recent Change in the Arctic Climate
Jennifer Francis

1:40 pm
Variability of Arctic Cloudiness from Satellite and Surface Data Sets
Axel J. Schweiger, Jeff Key, Xuanji Wang, Jinlun Zhang, Ron Lindsay

2:00 pm
Pan-Arctic Contaminant Landscapes: Status and Change
Jesse Ford, Derek Muir, Hans Borg, Maria Dam, Frank Riget, Natalia Ukraintseva

2:20 pm
Open Discussion

2:40 pm
Break

3:00 pm
Governing Large-Scale Control in Arctic Modelling
Hans von Storch

3:20 pm
Variability and Trends in the Arctic Climate as Simulated with the Bergen Climate Model
Tore Furevik, Asgeir Sorteberg, Mats Bentsen, Helge Drange, Nils Gunnar Kvamstø

3:40 pm
Polar Optimized WRF for Arctic System Reanalysis of Arctic Meteorology over Recent Decades
David H. Bromwich, Keith M. Hines

4:00 pm
Open Discussion

4:30 pm
Adjourn to Poster Session

Monday, 27 October 2003

Posters—Changes in the Atmosphere

Modeling Atmospheric Transport of Trace Pollutants to the Arctic: Source-to-Receptor Air Transfer Coefficient Maps: A Tool to Show How Changes in Weather, Climate and Emissions Can Change Contaminant Source Pathways and Deposition Patterns
Paul W. Bartlett, Kimberly Couchot

Core Atmospheric Measurements at the Summit, Greenland Environmental Observatory: GEOSummit
John F. Burkhart, Roger C. Bales, Joseph R. McConnell

The National Oceanic and Atmospheric Administration (NOAA) SEARCH Initiative
John Calder, Jackie Richter-Menge, Taneil Uttal, Jim Overland

FIRE.ACE Cloud Microphysical Observations and Their Parameterization: Emphases on Cloud Cover and Integration of Observations
Ismail Gultepe, George A. Isaac

The Urban Heat Island in Winter at Barrow, Alaska
Kenneth M. Hinkel, Frederick E. Nelson, Anna E. Klene, Julianne H. Bell

Arctic Modes of Temperature Variability During the Past 500 Years: Relating Summer to Winter.
Peter J. Huybers, Konrad A. Hughen, PARCS High-Resolution Working Group

Structure of Surface Level Pressure (SLP) Variability Over the Arctic for 1948–2001 and Future Climate Change
Oleg Y. Korneev

A Novel Analytical Approach Greatly Expands Ice Core Records of Climate Change and Industrial Pollution
Joseph R. McConnell, P. Ross Edwards, J. Ryan Banta, Diana Solter-Goss

The Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Project
Paul B. Shepson, Paty Matrai, Leonard A. Barrie, Jan W. Bottenheim

The Sensitivity of Arctic Climate Projections to the Initial State and Fate of the Theromhaline Circulation
Asgeir Sorteberg, Tore Furevik, Nils Gunnar Kvamsto, Helge Drange

Preliminary Studies of Regional Variability in Arctic Cloud Properties
Taneil Uttal

Using AVHRR Satellite Data to Investigate the Possible Effects of Dimethylsulfide Fluxes from a Coccolithophore Bloom on Regional Cloud Characteristics Over the SE Bering Sea
Bernard A. Walter

Development of Bias-Corrected Precipitation Database and Climatology for the Arctic Regions
Daqing Yang, Douglas Kane, David Legates, Barry Goodison

Monday, 27 October 2003

Parallel Science Session—Coastal Processes

(Marina Room)

Topics such as, but not limited to, fate and transport of materials, erosion, and effects on human communities.

Co-chairs: Volker Rachold, Alfred Wegener Institute
Steven Solomon, Natural Resources Canada

1:00 pm
Land-Shelf Interactions: An Update on Science Planning for Arctic Near-shore and Coastal Zone Research
Lee W. Cooper

1:10 pm
Arctic Coastal Dynamics (ACD) - Status Report
Volker Rachold

1:20 pm
International Polar Year 2007–2008: The Coastal Component
Sheldon Drobot, Chris Elfring

1:30 pm
Discussion: Programs and Overviews

1:45 pm
The Role of Sea Ice in Arctic Coastal Dynamics and Nearshore Processes
Hajo Eicken, Jerry Brown, Lee W. Cooper, Thomas C. Grenfell, Kenneth M. Hinkel, Andrew Mahoney, James A. Maslanik, Don K. Perovich, Craig Tweedie

1:55 pm
Storm Patterns in the Circumpolar Coastal Regime Derived from Observational Data, 1950–2000
David E. Atkinson, Steven M. Solomon

2:05 pm
Coastal Processes and Climate Change Along the Canadian Beaufort Sea
Steven Solomon, Gavin Manson

2:15 pm
Discussion: Physical Processes

2:30 pm
Break

3:00 pm
Missing Organic Carbon in the Coastal Kara Sea: Is Coastal Erosion a Significant Source?
Rainer M.W. Amon, Benedikt Meon

3:10 pm
Coastal Erosion and Nutrient Balance of the Arctic
Vladimir S. Stolbovoi

3:20 pm
Stable Carbon Isotopes in Sediments of The East-Siberian Sea: Connection with the Long-Term Water Mass Transport
Igor P. Semiletov, Oleg V. Dudarev, Kyung-Hoon Shin, Nori Tanaka

3:30 pm
Coastal Erosion Along the Alaskan Beaufort Sea Coast and Regional Estimates of Carbon Yields
Torre Jorgenson, Jerry Brown

3:40 pm
Discussion: Biogeochemical Processes

3:55 pm
General Discussion

4:30 pm
Adjourn to Poster Session

Monday, 27 October 2003

Posters—Coastal Processes

Contributions to Quaternary and Recent History of the Bering Sea Coast of Kamchatka, Russian Far East
Joanne Bourgeois, Tatiana Pinegina, Vera Ponomareva, Veronika Dirksen, Natalia Zaretskaia, Kevin Pedoja

Toward a Holocene Sediment Budget of the Central Kara Sea Shelf
Klaus Dittmers, Frank Niessen, Rüdiger Stein

Advection of Carbon on the Western Arctic Shelf: Implications for Benthic-Pelagic Coupling
Kenneth H. Dunton

Barrow Alaska: A Focal Point for Ice-Albedo-Transmission Feedback Studies of Arctic Sea Ice
Thomas C. Grenfell, Donald K. Perovich, Hajo Eicken

Geological and Geophysical Research into the Impact of Earthquakes on Prehistoric Coastal Occupation: The Mid-Holocene Occupation and Abandonment of the Tanginak Spring Site
Elizabeth Mahrt, Bretwood Higman, Joseph MacGregor, Joanne Bourgeois, Ben Fitzhugh

Long-Term Changes in Landfast Ice and Its Contribution to Shelf Freshwater
Yanling Yu, Harry L. Stern, Mark Ortmeyer

Tuesday, 28 October 2003

Parallel Science Session—Social Feedbacks

(Marina Room)

Co-chairs: Stewart Cohen, University of British Columbia and Environment Canada
Matthew Berman, University of Alaska Anchorage

1:30 pm
Introductory Remarks
Stewart Cohen, Matthew Berman

Part One: Projects Researching Adaptations to Climate Variations

1:40 pm
Understanding Human and Ecosystem Dynamics in the Arctic: The Imandra Watershed Project (Kola, Russia)
Alexey A. Voinov, Lars Bromley, Tatiana Moiseenko, Vladimir Selin

2:00 pm
The Influence of Environmental Conditions on the Success of Hunting Bowhead Whales Off Barrow, Alaska
Craig R. Nicolson, Craig George, Steve Braund, Harry Brower Jr.

2:20 pm
Climate System - Social System Interactions in the Northern Atlantic
Lawrence C. Hamilton

2:40 pm
Open Discussion: Status of Research on Social Feedbacks

2:50 pm
Break

Part Two: Panel on Programs Supporting Research on Social Feedbacks

3:00 pm
Detecting Change Through Community-Based Ecological Monitoring: Successful Examples of Systematic Local Knowledge Observation Systems
Gary P. Kofinas, Joan Eamer

3:15 pm
Shared Knowledge for Decision-Making on Environment and Health Issues in the Arctic
Nancy G. Maynard, Boris S. Yurchak

3:30 pm
Community-Defined Climate Change Impacts and Adaptation Research Needs in the Canadian North
Aynslie E. Ogden, Claire Eamer, Jamal Shirley, Steve Baryluk, Peter Johnson

3:45 pm
ArcticNet: The Integrated Natural/Health/Social Study of the Changing Coastal Canadian Arctic
Louis Fortier, Martin Fortier

4:00 pm
Panelist Discussion
Chair: Stewart Cohen
Panellists: Aynslie Ogden, Gary Kofinas, Nancy Maynard, Louis Fortier, Jamal Shirley

4:15 pm
Open Discussion: Research Programs

4:30 pm
Adjourn to Break

5:00 pm
Return to Plenary

Tuesday, 28 October 2003

Posters—Social Feedbacks

Adaptation and Sustainability in a Small Arctic Community: Results of an Agent-Based Simulation Model
Matthew Berman, Craig Nicolson, Gary Kofinas, Stephanie Martin

Increased Fall Storminess, Threats to Public Infrastructure, and the Effects on Fall Whaling in Barrow, Alaska
Anne M. Jensen, Eugene Brower, J. Craighead George, Robert Suydam

Late Holocene Environmental Change in SW Greenland and the Fate of the Norse
Naja Mikkelsen, Antoon Kuijpers

The Continuation of "Contemporary Ideas of Nature and Civilization's Prospects for Countermeasures"
Vladimir F. Sevostianov

Arctic Climate Research and Traditional Ecological Knowledge: The Quantitative Aspect of TEK
Raphaela Stimmelmayr

Adjustment to Reality - Cases of Detached, Dependent, and Sustained Community Development in Greenland
Daniela Tommasini, Rasmus O. Rasmussen

Tuesday, 28 October 2003

Posters—Human/ Environment Interactions

Modeling Impacts of Hydrologic and Climatic Change on Humans in the Arctic
Lilian Alessa, Daniel White, Larry Hinzman, Peter Schweitzer

The Common Raven (*Corvus corax*) on the North Slope of Alaska: Wildlife Management and the Human Dimension
Stacia A. Backensto

Shaking Up the Neighborhood: Historic Perspective on Resilience and Vulnerability in the Gulf of Alaska
Jennie N. Deo, Catherine W. Foster, Margaret R. Berger, Ben Fitzhugh

Human Impacts to Fire Regime in Interior Alaska
La'ona DeWilde

The Archeology of Glaciers and Snow Patches: A New Research Frontier
E. James Dixon, William F. Manley, Craig M. Lee

Analyzing the Implications of Climate Change Risks for Human Communities in the Arctic: A Vulnerability-Based Approach
James D. Ford, Barry Smit

Tuesday, 28 October 2003

Parallel Science Session—Biological Feedbacks

(Sound Room)

Co-chairs: Joshua Schimel, University of California Santa Barbara
Sue Moore, National Oceanic and Atmospheric Administration

1:30 pm
Session Introduction: Terrestrial Feedbacks vs. Marine Case Studies
Joshua Schimel

1:40 pm
Potential Arctic Terrestrial Ecosystem Feedbacks to Climate Change: A Consideration of Component Carbon Pool Dynamics
Paul Grogan, Sven Jonasson

2:00 pm
Modeling Modes of Variability in Carbon Exchange Between High Latitude Terrestrial Ecosystems and the Atmosphere: A Synthesis of Progress and Identification of Challenges
Anthony D. McGuire, Joy S. Clein, Qianlai Zhuang

2:20 pm
Question and Answer / Discussion Period

2:30 pm
A Critical Review of the "Regime Shift/Junk Food" Hypothesis for the Steller Sea Lion Decline
Lowell W. Fritz, Sarah Hinckley

2:45 pm
Linkages Among Climate, Growth, Competition at Sea, and Production of Sockeye Salmon Populations in Bristol Bay, Alaska, 1955–2000
Jennifer L. Nielsen, Gregory T. Ruggerone

3:00 pm
Break

3:15 pm
Ringed Seals and Changing Snow Cover on Arctic Sea Ice
Brendan P. Kelly, Oriana R. Harding, Mervi Kunnasranta

3:30 pm
Increasing Sea Ice in Baffin Bay and Adjacent Waters Threatens Top Marine Predators
Mads Peter Heide-Jørgensen, Kristin L. Laidre

3:45 pm
Multi-Decadal Response of a Seabird to the Arctic Oscillation
George Divoky

4:00 pm
Discussion and Poster Review
Sue Moore

5:00 pm
Return to Plenary

Tuesday, 28 October 2003

Posters—Biological Feedbacks

Climate, Snow, and Hydrology in Tundra Ecystems: Patterns, Processes, Feedbacks, and Scaling Issues
Bob Baxter, Brian Huntley, Richard Harding, Terry V. Callaghan

Plant and Soil Responses to Neighbor Removal and Fertilization in Acidic Tussock Tundra
Syndonia Bret-Harte, Erica A. Garcia, Vinciane M. Sacré, Joshua R. Whorley, Joanna L Wagner, Suzanne C. Lippert, Terry Chapin

Effects of Canopy Representation on Carbon Balance Simulations at Treeline
David M. Cairns

The Effects of Soil Moisture on Carbon Processes in Upland and Lowland Tundra Ecosystems
Faith A. Heinsch, John S. Kimball, Sinkyu Kang, Hyojung Kwon, Walter C. Oechel

Paleo-Investigations of Climate and Ecosystem Archives (PICEA): Holocene Fire and Vegetation History from Ruppert Lake, Brooks Range, Alaska
Philip Higuera, Linda B. Brubaker, Patricia M. Anderson, Feng Sheng Hu, Ben Clegg, Tom Brown, Scott Rupp

Feeding on the Bottom at the Top of the World
Katrin B. Iken, Bodil A. Bluhm, Rolf R. Gradinger

Non-invasive, Highly Resolved Observations of Sea Ice Biomass Dynamics: A Link Between Biogeochemistry and Climate
Christopher Krembs, Klaus Meiners, Dale Winebrenner

Using Gray Whales to Track Climate Change in the Alaskan Arctic
Sue E. Moore, Jacqueline M. Grebmeier

Commander Islands as the Significant Point for Monitoring Some Dangerous Changes in Beringia Ecosystem
Vladimir F. Sevostianov

Seasonal and Non-linear Effects of Experimental Climate Change on High-Arctic Ecosystem Carbon Exchange
Heidi Steltzer, Jeff Welker, Paddy Sullivan

The Impact of Snow-up Timing on Arctic Winter Soil Temperatures
Matthew Sturm, Glen E. Liston, Charles Racine

The Effect of Temperature, Water Content, and Light Intensity and Quality on Nitrogen Fixation in High Arctic Tundra Vegetation
Matthias Zielke, Rolf A. Olsen, Bjørn Solheim

Tuesday, 28 October 2003

Parallel Science Session—Physical Feedbacks

(Bay Auditorium)

Co-chairs: Michael Steele, University of Washington
Stephen Vavrus, University of Wisconsin

1:30 pm
Introduction

1:40 pm
The Influence of Cloud Feedbacks on Arctic Climate Change
Steve Vavrus

1:50 pm
Atmospheric Heat Transport as a Feedback on the Arctic Climate
Cecilia M Bitz, Stephen J. Vavrus

2:10 pm
The Role of Surface Albedo Feedback in Climate
Alex Hall

2:30 pm
The Ice-Albedo Feedback in a Changing Climate: Albedos from Today and Reflections on Tomorrow
Don Perovich

2:50 pm
The Ice/Ocean Interface During Summer: Implications for Ice-Albedo Feedback
Miles G. McPhee

3:10 pm
A Data-Model Comparison Study of the Arctic Ocean's Response to Annular Atmospheric Modes
Bruno Tremblay, Robert Newton, Peter Schlosser

3:30 pm
Open Discussion

4:30 pm
Adjourn to Break

5:00 pm
Return to Plenary

Tuesday, 28 October 2003

Posters—Physical Feedbacks

Using a Spatially Distributed Model to Characterize the Influence of Permafrost on Hydrological Processes
William R. Bolton, Larry D. Hinzman, Scott Peckham, Douglas L. Kane, Kenji Yoshikawa

Observed and Modeled Relationships Among Arctic Climate Variables
Yonghua Chen, James R. Miller, Jennifer A. Francis, Gary L. Russell, Filipe Aires

Fram: A New Basin-Scale Model of Sea Ice Dynamics
Max Coon

Evaluation of the True Ice Mass in the Arctic Ocean
Nikolay Doronin

The Role of Sea Ice Mechanics and Deformation in Arctic Climate Change
William D. Hibler III, Erland M. Schulson

Variability in Simulated Arctic Freshwater Budgets
Marika M. Holland, Joel Finnis

An Eddy-admitting Global Ice-ocean Simulation
Elizabeth C. Hunke, Mathew Maltrud, Rainer Bleck

Field Studies on Basin Scale Water Balance on North Slope, Alaska
Danielle C. Kitover, Doug Kane, Rob Gieck, Larry Hinzman

The Physical and Hydrological Impacts of a Wildfire on an Arctic Tundra Ecosystem, Seward Peninsula, Alaska
Stefan Kooman, Larry D. Hinzman

Laboratory-Based Studies of the Physical and Biological Properties of Sea Ice: A Tool for Understanding Physical Processes and Feedback Mechanisms in the Arctic
Bonnie Light, Christopher Krembs

Improving Arctic Snow-Related Features Within Regional Climate Models
Glen E. Liston, Matthew Sturm

Assimilation of Satellite Ice Concentration Data in a Coupled Ice-Ocean Model for the Arctic Ocean, Using the Ensemble Kalman Filter
Julia B. Rosanova

The Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Project
Paul B. Shepson, Paty Matrai, Leonard A. Barrie, Jan W. Bottenheim

Possible Feedbacks on Arctic Cloud Formation: Can the Arctic Biosphere Affect the Melting of the Ice?
Michael Tjernström, Caroline Leck

DOE-ARM Science at the North Slope of Alaska Site
Johannes Verlinde, Jerry Harrington, Eugene Clothiaux, Scott Richardson, Chad Bahrmann, Bernie Zak

The Expanded Regional Integrated Monitoring System (E-RIMS) for Pan-Arctic Water System Studies: Project Overview
Charles J. Vörösmarty, Mark Serreze, Michael Steele, Richard B. Lammers, Mark Fahnestock, Steve Frolking, Ernst Linder, Michael Rawlins, Alexander I. Shiklomanov, Richard Armstrong, Christoph Oelke, Tingjun Zhang, Jinlun Zhang, Robie McDonald, Igor A. Shiklomanov, Cort J. Willmott

Exchanges Between the Arctic and Atlantic Oceans in a Global Ice-Ocean Model
Jinlun Zhang, D. Andrew A. Rothrock, Mike Steele

Tuesday, 28 October 2003

Parallel Science Session—Drivers and Causes

(Cove Room)

Co-chairs: James Overland, National Oceanic and Atmospheric Administration
Mark Serreze, University of Colorado

1:00 pm
Relationships Between Understanding Unaami and Predicting the Arctic System
Richard E. Moritz

1:20 pm
Solar-Induced Cyclic Variations of Holocene Climate and Ecosystems in a High-Latitude Region of the North Pacific
Feng Sheng Hu, Darrell Kaufman, Sumiko Yoneji, David Nelson, Aldo Shemesh, Yongsong Huang, Jian Tian, Gerard Bond, Benjamin Clegg, Thomas Brown, Jason Lynch, Andrea Hui

1:40 pm
Stratosphere/Troposphere Coupling and Effects on High-Latitude Climate
Mark P. Baldwin

2:00 pm
Arctic Ocean Change: What Changes and What Doesn't (Almost)
Greg Holloway

2:20 pm
Break

2:40 pm
Toward a Regional Arctic Climate Model for SEARCH
Wieslaw Maslowski

3:00 pm
Arctic Ocean and Sea Ice Changes, Greenhouse Forcing, and the Arctic Oscillation
John W. Weatherly

3:20 pm
The Ecology and Paleoecology of Human-Landscape Interactions on the North Pacific and Southern Bering Sea: Investigating the Role of the Aleut as Ecosystem Engineers
Herbert D.G. Maschner, James W. Jordan, Nancy Huntly, Bruce P. Finney, Katherine L. Reedy-Maschner

3:40 pm
Searching for Bellwethers in Changing Arctic Environments: Some Cautionary Notes
David W. Norton

4:00 pm
Discussion

5:00 pm
Return to Plenary

Tuesday, 28 October 2003

Posters—Drivers and Causes

Fresh Water Content Variability in the Arctic Ocean
Sirpa Hakkinen, Andrey Y. Proshutinsky

Holocene Thermal Maximum in the Western Arctic
Darrell Kaufman, PARCS Holocene Thermal Maximum

Preliminary Volume Transports through Nares Strait, Summer 2003
Andreas Muenchow

Changes in the Presence of Mussels (*Mytilus spp.*) and Macroalgae in Arctic Alaska: Re-evaluating Evidence Used to Relate Bivalve Presence to Climate Change.
David W. Norton

Velocity Estimates for Ice
Drifting in Alaska's Northern Chukchi Sea Flaw Zone During Spring Subsistence Whaling Seasons of 2000 and 2001: Climate Change Implications?
David W. Norton, Allison M. Graves

Surface Energy Budget Requirements for Pack Ice Change Attribution During SEARCH
Ola P. Persson

A New Sea Ice Model for the Marginal Ice Zone
Matthew J. Pruis, Max Coon, Leif Toudal, Ted Maksym, Gad Levy

Monitoring Pan-Arctic Snowmelt Hydrology Using Active Radar
Michael A. Rawlins, Kyle C. McDonald, Richard B. Lammers, Steve Frolking, Mark Fanhstock, Charles J. Vörösmarty

Response of the Pan-Arctic Ice-Ocean Climate to Atmospheric Circulation Regimes
Jia Wang, Bingyi Wu, Meibing Jin, John Walsh, Motoyoshi Ikeda

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