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Study of Environmental Arctic Change

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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.

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.

Session Summary: Changes in the Atmosphere

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 20th 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.

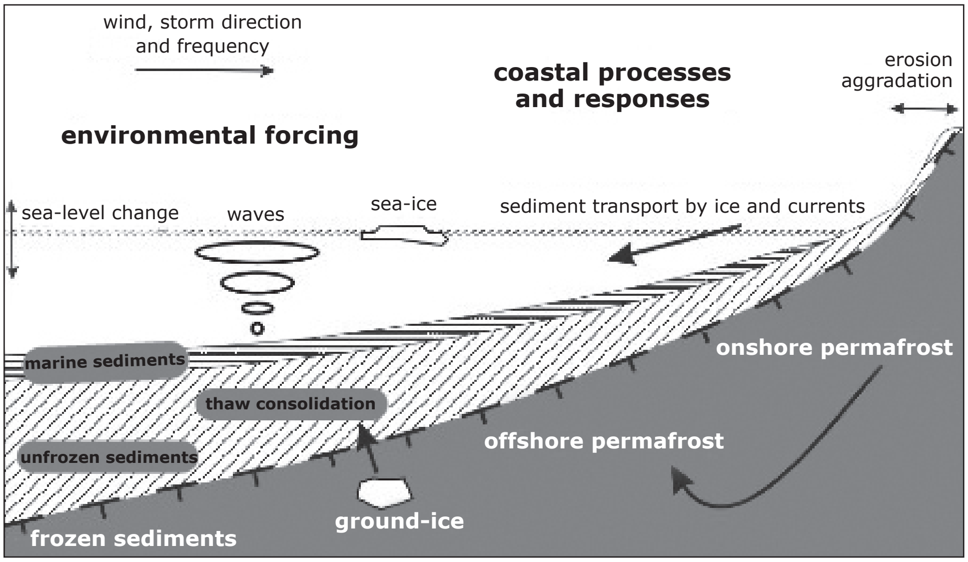

Figure 1. Arctic coastal processes and responses to environmental forcing.

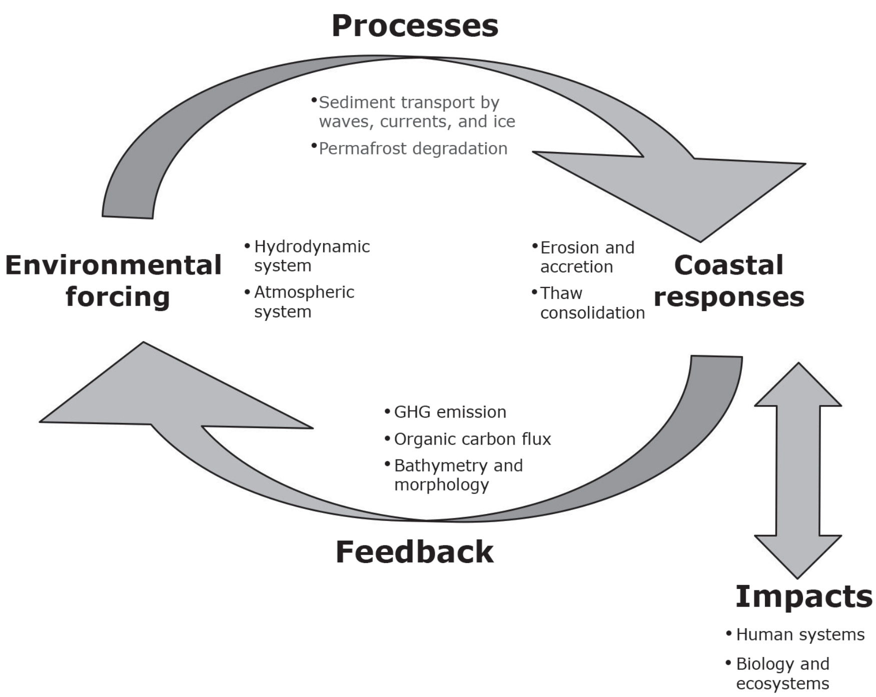

Figure 2. Environmental forcing, coastal processes and responses, impacts, and feedback.

Session Summary: Social Feedbacks

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.

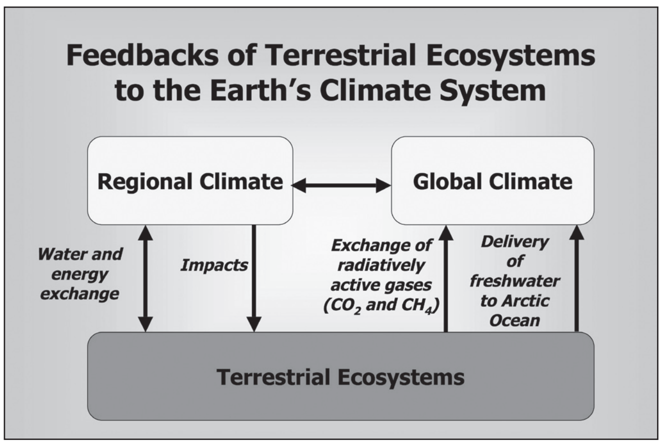

Figure. Feedbacks of the terrestrial ecosystems to the Earth's climate system. From McGuire et al.

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.

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.

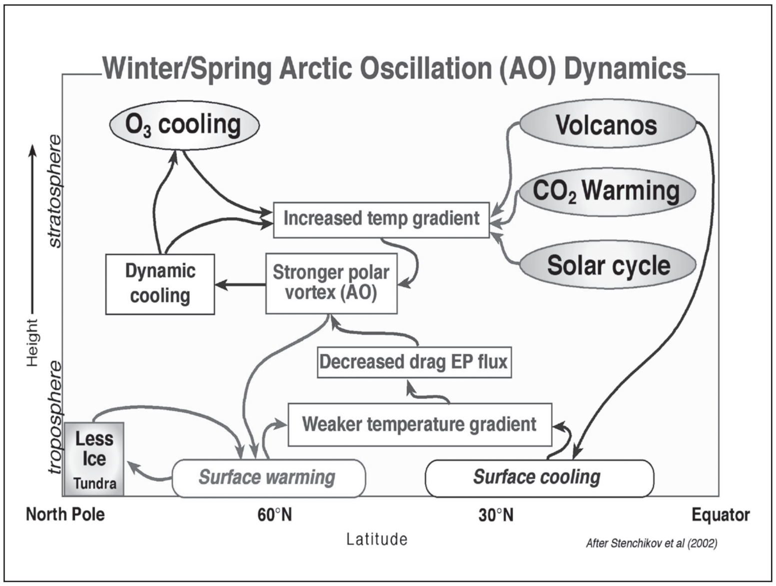

Figure. Winter/spring Arctic Oscillation dynamics.