The Hydrologic Cycle and its Role in Arctic and Global Environmental Change:

A Rationale and Strategy for Synthesis Study

A Report from the Scientific Community to the
National Science Foundation Arctic System Science Program

NSF-ARCSS Hydrology Workshop Steering Committee

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—Charles Vörösmarty and Larry Hinzman, co-chairs
NSF-ARCSS Hydrology Workshop Steering Committee

Executive Summary

with Key Findings and Recommendations

The arctic system constitutes a unique and important environment with a central role in the dynamics and evolution of the earth system. The Arctic is inherently a highly dynamic system. Yet there is mounting evidence that it is now experiencing an unprecedented degree of environmental change. Many of these changes are linked to the arctic hydrologic cycle and are quite possibly the result of both the direct and indirect impacts of human activities. Despite the importance of this issue, the current state of the art cannot adequately establish these potential linkages to global change. Understanding the full dimension of arctic change is a fundamental challenge to the science community over the coming decades and will require a major new effort at interdisciplinary synthesis. It also requires an unprecedented degree of international cooperation.

Current State of the Art

The water cycle is an inseparable element of the climate, biology, and biogeochemistry of the arctic region. The sensitivity of arctic hydrology to environmental change has been demonstrated through dozens of disciplinary studies focused on individual elements of the water cycle such as precipitation, evaporation, or runoff. We know much less about water-related teleconnections to regional and global climate. The absence of cross-disciplinary synthesis studies contributes to our inability to formulate a clear and quantitative picture of the integrated arctic system. In the face of global environmental change, the arctic science community has made predictions of system-wide impacts, but with little confidence.

These key, unresolved issues can be cast as a set of scientific questions, fundamentally cross-disciplinary and synthetic in nature:

- **What are the major features (i.e., stocks and fluxes) of the pan-arctic water balance and how do they vary over time and space?**

- **How will the arctic hydrologic cycle respond to natural variability and global change?**

- **What are the direct impacts of arctic hydrology changes on nutrient biogeochemistry and ecosystem structure and function?**

- **What are the hydrologic cycle feedbacks to the oceans and atmosphere in the face of natural variability and global change? How will these feedbacks influence human systems?**

Key Scientific Challenges and Recommendations

How well are we poised to answer such questions? A survey of the arctic science community—represented by an interdisciplinary workshop convened by ARCSS in September 2000 and summarized in the remainder of this volume—revealed 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. Three major research and synthesis challenges with accompanying recommendations for strategic investments in arctic system science are given below. Understanding, simulating, and predicting contemporary and future hydrological dynamics is greatly limited by:

1. A ***sparse observational network*** for routine monitoring together with the absence of integrated data sets of spatial and temporally harmonized biogeophysical information over the pan-arctic domain. The situation is far from optimal and deteriorating rapidly over much of the pan-arctic, especially in Russia and Canada.

Recommendations: A substantial commitment should be made to rescue, maintain, and expand current meteorological and hydrological data collection efforts. Establishing high-resolution gridded maps of climatic, hydrologic, topographic, vegetation, and soil property attributes for the Arctic Ocean watershed is strongly advised. Additional resources must be invested in scaling techniques, including the expanded use of remote sensing. Support for free and open access to arctic environmental data sets is essential to future progress. Coordination with existing U.S. and international monitoring programs is critical.

2. Numerous ***gaps in our current understanding of basic scientific principles and processes*** regarding the water cycle over the entire pan-arctic domain.

Recommendations: Interdisciplinary synthesis studies linking hydrologic processes with other dependent biogeochemical and biogeophysical processes should be fostered to assemble a more complete understanding of the arctic system and its role in the broader earth system. Investments in long-term, process-based hydrological field studies are required.

3. The ***lack of cross-disciplinary synthesis research and modeling*** to decipher feedbacks arising from arctic hydrological change on the earth system and on society.

Recommendations: Support should be given to integrative research that identifies the unique role of arctic hydrosystems in the broader earth system. An assessment of the feedback mechanisms through which progressive hydrological change influences both natural and human systems is urgently needed. New research devoted to establishing quantitative linkages between the biogeophysical and socioeconomic research communities is strongly advised.

Major New Synthesis Initiative Required

The gaps identified above demonstrate an urgent need to reformulate the manner in which arctic hydrological research is funded and executed. Implementation of the recommended actions will require a dedicated research program to support arctic hydrological synthesis studies. Such a program does not now exist, yet has been called for as a component of the U.S. Global Change Research Program's initiative on the water cycle. To support this new science, the committee's central recommendation is that:

- **NSF-ARCSS invest in the development of a *pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP)* to provide a framework for integration studies of the pan-arctic water cycle and to articulate the role of freshwater in terrestrial ecosystem, biogeochemical, biogeophysical, ocean, climate, and human dynamics.**

The primary aim of Arctic-CHAMP is to catalyze and coordinate interdisciplinary research with the goal of constructing a holistic understanding of arctic hydrology through integration of routine observations, process-based field studies, and modeling. Four goals should guide this effort:

Goal 1: Assess and better understand the stocks and fluxes which constitute the arctic hydrologic cycle.

Goal 2: Document changes to the arctic water cycle, contributing a hydrological component to the multiagency SEARCH Program.

Goal 3: Understand the causes of arctic water cycle change and assess their direct impacts on biological and biogeochemical systems.

Goal 4: Develop predictive simulations of the response of the earth system and human society to feedbacks arising from progressive changes to arctic hydrological systems.

Implementation of Arctic-CHAMP

To execute this initiative, the committee strongly recommends:
- creating an Arctic-CHAMP Scientific Steering Committee (AC-SSC) to formulate a detailed interdisciplinary implementation plan and then supervise execution of the initiative
- supporting a multidisciplinary set of process-based catchment studies
- initiating a major effort to improve our current monitoring of water cycle variables, coordinating with U.S. and international agency partners as required
- establishing the Arctic-CHAMP Synthesis and Education Center

(CSEC) to serve as the physical location for several of the scientific activities of the program. The center should lead the coordination of modeling, field research, and monitoring efforts within CHAMP.

- selecting a core group of Arctic-CHAMP researchers, chosen through peer review, to execute process studies, monitoring, and modeling efforts. The research team would include principal investigators and their post-doctoral fellows and graduate students, in residence at CSEC. The team would have representatives from the biogeophysical and socioeconomic realms and include both observationalists and modelers.
- convening an Arctic-CHAMP Workshop Series and Open Science Meetings to promote a continuing involvement of the arctic and earth systems science communities
- fostering collaboration with the many relevant U.S. arctic research initiatives. This will help to ensure maximum synergy across programs and avoid duplication of effort. The hydrologic cycle studies of Arctic-CHAMP could serve as the NSF-ARCSS contribution to the multiagency SEARCH Program. They also will support NSF Biocomplexity and Information Technology programs as well as public outreach and education efforts.
- creating and sustaining a vigorous set of international science and monitoring partnerships. Most of the pan-arctic land mass resides in Russia and Canada. No single National Science Foundation program, or even the U.S. arctic research community as a whole, could achieve the degree of synthesis required. The NSF must forge strategic international partnerships to be successful in this endeavor.

Policy Implications

Scientists have yet to observe and understand the full dimension of pan-arctic variability and progressive change, but at the same time, they are under increasing pressure to advise the policy-making community as it struggles with how best to manage the full dimension of contemporary and future global change. The impact of arctic system change is likely to extend far beyond the Arctic per se and thus become of critical concern to society at large. An investment in knowledge is of clear and immediate necessity. The contributions of an Arctic-CHAMP toward articulating the diverse physical, biological, and human vulnerabilities to this change provide an important impetus for international cooperation in wisely managing this critical part of the earth system.

Key Unresolved Scientific Questions

- **What are the major features (i.e., stocks and fluxes) of the pan-arctic water balance and how do they vary over time and space?**
- **How will the arctic hydrologic cycle respond to natural variability and global change?**
- **What are the direct impacts of arctic hydrology changes on nutrient biogeochemistry and ecosystem structure and function?**
- **What are the hydrologic cycle feedbacks to the oceans and atmosphere in the face of natural variability and global change? How will these feedbacks influence human systems?**

Recommendations

- A substantial commitment should be made to ***rescue, maintain, and expand data collection efforts***. Establishing high-resolution gridded maps of climatic, hydrologic, topographic, vegetation, and soil property attributes for the Arctic Ocean watershed is strongly advised. Additional resources must be invested in scaling techniques, including the expanded use of remote sensing.

- ***Interdisciplinary synthesis studies*** linking hydrologic processes with other dependent biogeochemical and biogeophysical processes should be fostered. Investments in long-term, process-based hydrological field studies are required.

- Support ***integrative research*** that identifies the unique role of arctic hydrosystems in the broader earth system.

- Develop a ***pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP).***

Arctic-CHAMP Implementation

- Create an *Arctic-CHAMP Scientific Steering Committee (AC-SSC)* to formulate a detailed interdisciplinary implementation plan and then supervise execution of the initiative.

- Support a multidisciplinary set of ***process-based catchment studies***.

- Initiate a major effort to ***improve our current monitoring of water cycle variables***, coordinating with U.S. and international agency partners as required.

- Establish the *Arctic-CHAMP Synthesis and Education Center (CSEC)* to serve as the physical location for several of the scientific activities of the program. The center should lead the coordination of modeling, field research, and monitoring efforts within CHAMP.

- Convene an *Arctic-CHAMP Workshop Series and Open Science Meetings* to promote a continuing involvement of the arctic and earth systems science communities.

- ***Foster collaboration with*** the many relevant ***U.S. arctic research initiatives.*** The hydrologic cycle studies of Arctic-CHAMP could serve as the NSF-ARCSS contribution to the multiagency SEARCH Program. They also will support NSF Biocomplexity and Information Technology programs and public outreach and education efforts.

- Create and sustain a vigorous set of ***international science and monitoring partnerships.*** The NSF must forge strategic international collaborations to achieve the degree of synthesis required.

1
Introduction

The water cycle of the Arctic plays a central role in regulating both the planetary heat balance and circulation of the global oceans. Recent and unprecedented environmental changes, such as declines in the total area of winter snow cover on land and declining sea ice cover throughout the Arctic Ocean, are now well documented. Unfortunately, the causes of these changes and their impact on the global ocean and atmosphere are still poorly understood. The cycle of freshwater in the arctic land-atmosphere-ocean system is central to these observed changes (Figure 1-1). Yet, knowledge of the hydrology of the arctic region remains incomplete due to the complexities of permafrost terrain, difficulties in acquiring data in harsh environments, decline in routine monitoring, and a lack of interdisciplinary research. Progress in predicting global change can only be achieved through development of a new more synthetic and systematic understanding of the water cycle of the Arctic.

In September of 2000, a workshop supported by the National Science Foundation Arctic System Science (ARCSS) Program was convened at the National Center for Ecological Analysis and Synthesis in Santa Barbara, California. The workshop's central goal was to:

- ***Assess the state of the art in arctic systems hydrology and identify research priorities for achieving predictive understanding of the role of the arctic water cycle in global change.***

The meeting had broad representation from within the arctic research community, with more than 30 members having expertise in land surface hydrology, terrestrial and freshwater ecology, atmospheric dynamics, ocean processes, simulation modeling and geo-spatial analysis (Appendix 1). A steering committee attempted to capture consensus views articulated during the meeting and represented by this current document. Major thrusts of the workshop were to articulate the need for interdisciplinary arctic hydrologic studies and to formulate a strategy for new synthesis research.

Rationale for Pan-Arctic Hydrologic Synthesis

The pan-arctic hydrological system is complex and currently undergoing a period of rapid change that will influence all aspects of life in the Arctic. The changes will also interact in important ways with the global system. In the following chapters, we document these changes and show the complex linkages within the arctic hydrologic system and between the arctic and global systems. If we are to understand the rapidly changing state of the Arctic and predict its future condition, we need to synthesize existing hydrologic knowledge and to identify gaps in that knowledge. It is critical to organize our current understanding into a framework that captures the essential workings and complexities of the arctic water cycle, taken as a whole. In this way we can more effectively articulate the Arctic's unique place within the larger earth system and its role in global change, as called for in the recent U.S. Global Change Research Program water cycle initiative (USGCRP Water Cycle Study Group 2001).

An understanding of the contemporary and potential future states of the arctic hydrological system is a precursor to assessments of the associated impact on natural ecosystems and human society. Such assessments must rely on high quality, quantitative information and are thus critical to sound policies for environmental protection.

The Arctic Water Cycle as an Integrating Framework

The hydrologic cycle provides an ideal framework for arctic system synthesis. First, the arctic hydrologic system spans three realms: land, ocean, and atmosphere. Second, the water cycle is more than just a set of physical processes: it includes living things—plant, animal, and human—and they all interact. Third, the hydrologic cycle is a complex system that cannot be understood or predicted from study of its individual parts alone (Woo 1986). This complexity exists over the pan-arctic scale down to the smallest river basin or research plot.

The arctic domain may be one of the best places to explore the interaction of land, atmosphere, and oceans through the unique role that water plays in linking these realms (Figures 1-1 and 1-2). It is the most "closed" and land-dominated of all the major ocean basins (Vörösmarty et al. 2000). The Arctic Ocean's connection to global ocean circulation is through two relatively well-defined exchanges through the Bering Strait and Nordic Sea. Sea ice generated in the Arctic Ocean can be tracked on its way southward to the Atlantic. Atmospheric exchange is bounded by the fairly well-identified Polar Front. The domain is relatively pristine, and thus an excellent laboratory for isolating the effects of natural variability versus the direct impacts of human activity.

Current Arctic Water Cycle Research

Although there is a widespread recognition that arctic hydrology is sensitive to global change, an understanding of the basic mechanisms that control terrestrial water cycling constitutes a major research need. Recent ARCSS activities have clearly identified the importance of the terrestrial water cycle, reflected most notably in the LAII *Plan for Action* (1997), *Modeling the Arctic System* (1997), *Toward an Arctic System Synthesis* (1998), and *Toward Prediction of the Arctic Sys-*

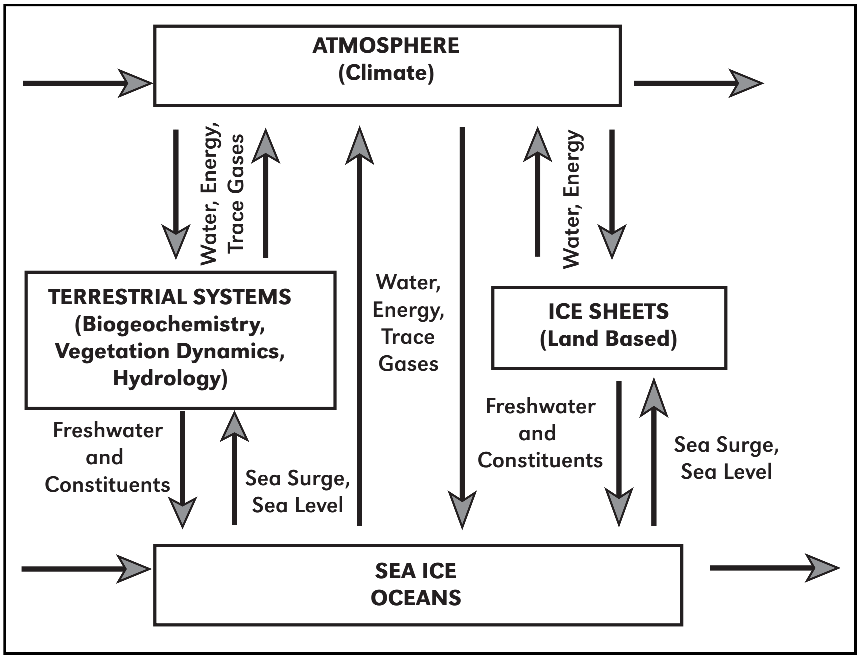


Figure 1-1. Conceptual diagram of the arctic system, showing linkages among the atmosphere, land surface, and ocean systems. Links within the arctic region as well as the larger earth system must be considered to achieve an integrated view of the hydrological cycle (from Walsh et al. 2001).

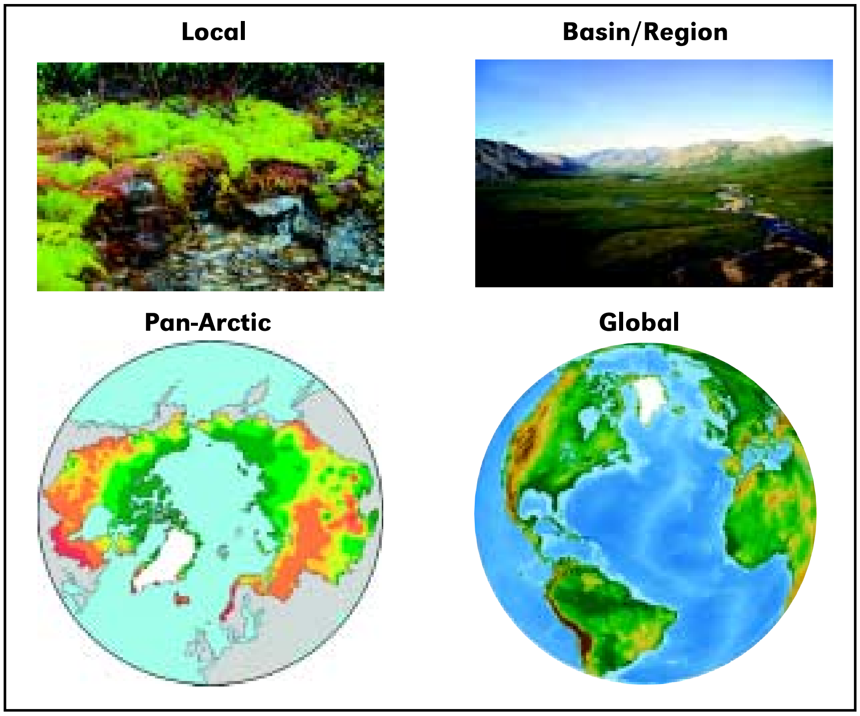


Figure 1-2. Multiscale approach toward achieving synthesis of pan-arctic hydrological dynamics and identifying its role in the larger earth system. Information from all scales is necessary to ensure mutual consistency of predictive models. Biophysical, biogeochemical, and human dimension issues should be simultaneously addressed. (Precipitation over the land area that drains into the Arctic Ocean is shown in the lower left panel.)

tem (1998) workshop reports and steering documents. Many of the overview diagrams in these publications show elements of the terrestrial water cycle figuring prominently in virtually all arctic system dynamics. Although these reports recognize a key role for water in the arctic system, there remains a compelling need for a coherent framework through which to study arctic hydrology per se.

A proliferation of traditional disciplinary research has been successful in producing a wealth of knowledge about individual components of the hydrologic system (Brown 1968, Dingman 1973, Dingman et al. 1980). However, this body of work does not yet permit these pieces to be forged into a comprehensive understanding of the whole. Work funded by NSF and other agencies has typically been separated by discipline—hydrology, atmosphere and ocean dynamics, biogeochemistry, and ecology—and collaboration between the disciplines has been limited. Essential hydrologic processes regulating terrestrial ecosystem dynamics, for example, have often been addressed through independent hydrologic studies and have not taken advantage of the synergy possible by the sharing of research sites and experimental design. But the interfaces between these disciplines are likely to be the very areas where the most exciting and valuable new research will take place. Disciplinary barriers need to come down.

The Need for Synthesis

In developing an integrated picture of arctic hydrology, the scientific community has at its disposal a broad disciplinary literature that can provide a quantitative summary of the pools of water and energy found in the atmosphere, soil, rivers, lakes, glaciers, sea ice, and ocean waters of the Arctic (Figure 1-3). Estimates of the energy and water transport into and out of the Arctic are also becoming available. While providing a useful backdrop, collectively these studies are hardly comprehensive and difficult to interpret from a systems viewpoint. Because of its integrating role, the arctic water cycle requires an understanding of the processes controlling these pools and transports. An integrated scientific program based on long-term monitoring, field studies, and simulation could provide an important path forward. We would be in a much improved position to assess and interpret historic trends and to make predictions of the future.

Development of a synthetic understanding of the arctic hydrologic cycle will thus require closer collaboration between modelers and observationalists. Field measurements and process studies provide the data and physical insights for arctic water cycling that underpin modeling efforts. Models, in turn, provide predictive capability, the critical ability to extrapolate in time and space needed to address the impact of hydrologic change. Models have not yet been adequately exploited in designing optimal arctic monitoring programs, identifying regions where the density and distribution of critical measurements need to be upgraded, or singling out significant gaps in our understanding of the hydrologic processes. A multidisciplinary approach can yield important new insights (Figure 1-4). Communication and close collaboration between these groups is essential.

NSF-ARCSS Hydrology Workshop participants proposed a major scientific challenge:

- ***Can we successfully construct a quantitative and coherent picture of the arctic water cycle and its links to the earth system based on the current state of knowledge, infrastructure, and institutional support, including all relevant ARCSS and non-NSF research programs?***

A consensus indicated that the answer is ***no.*** Three major obstacles have hindered progress:

1. A ***sparse observational network*** for routine monitoring together with the absence of integrated data sets of spatial and temporally harmonized biogeophysical information over the pan-arctic domain.
2. Numerous ***gaps in our current understanding of basic scientific principles and processes*** regarding water cycling in arctic environments.
3. The ***lack of cross-disciplinary synthesis research and modeling*** to decipher feedbacks on the earth system and on society arising from arctic hydrological change.

To address these challenges, the workshop participants recommended development of a pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) that focuses on arctic water and energy cycles. Arctic-CHAMP is planned as a research program with routine

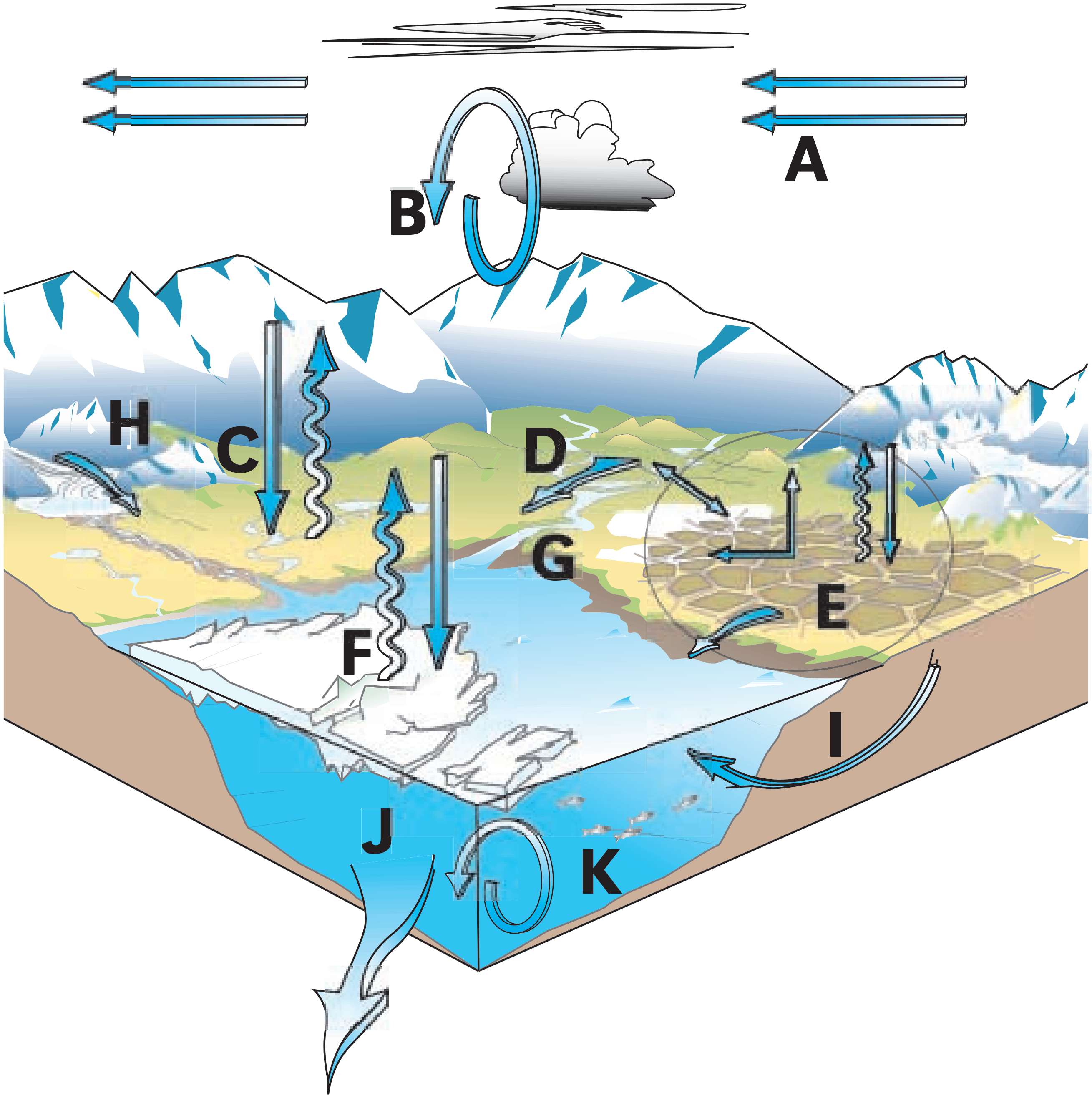


Figure 1-3. Conceptual model of the arctic hydrological cycle, with key linkages among land, ocean, and atmosphere. The coupling of these components within the Arctic and to the larger earth system remains an important yet unresolved research issue. The hydrological cycle is inextricably connected to all biological and chemical processes occurring in the biosphere, atmosphere, and cryosphere. Hydrologic interactions with terrestrial and aquatic ecosystems and their biogeochemistry control all life in arctic regions.

A = *atmospheric boundary fluxes*
B = *atmospheric dynamics*
C = *land-surface atmosphere exchanges (with vegetation and permafrost dynamics)*
D = *discharge through well-defined flow networks (with groundwater and river corridor flow)*
E = *runoff from poorly organized lowland flow systems*
F = *sea ice mass balance and dynamics*
G = *estuarine controls on terrestrial/shelf interactions*
H = *changes in glacial mass balance and associated runoff*
I = *direct groundwater discharge to ocean*
J = *Arctic Ocean dynamics and deep water formation*
K = *biological dynamics and oceanic food chains*

observations, focused on process-based field studies, and pan-arctic synthesis. The workshop participants went on to develop a conceptual framework for Arctic-CHAMP and to define its role within NSF-ARCSS.

Report Framework

In the chapters that follow we explain the scientific reasoning for Arctic-CHAMP together with several practical aspects surrounding its implementation. We begin with a chapter describing the conceptual design of the Arctic-CHAMP. This chapter is followed by a summary of our current state of knowledge regarding the arctic water cycle and its role in climate, land, and ocean system dynamics. We then show evidence for changes to the arctic water cycle. A chapter is then presented which is organized as a brief assessment of our current understanding of the sensitivity of arctic hydrology to global change and of the potential feedbacks to the larger pan-arctic and earth systems. We close with an initial set of recommendations for implementation of Arctic-CHAMP, highlighting opportunities for collaborative work with other U.S. and international agency partners across the Arctic.

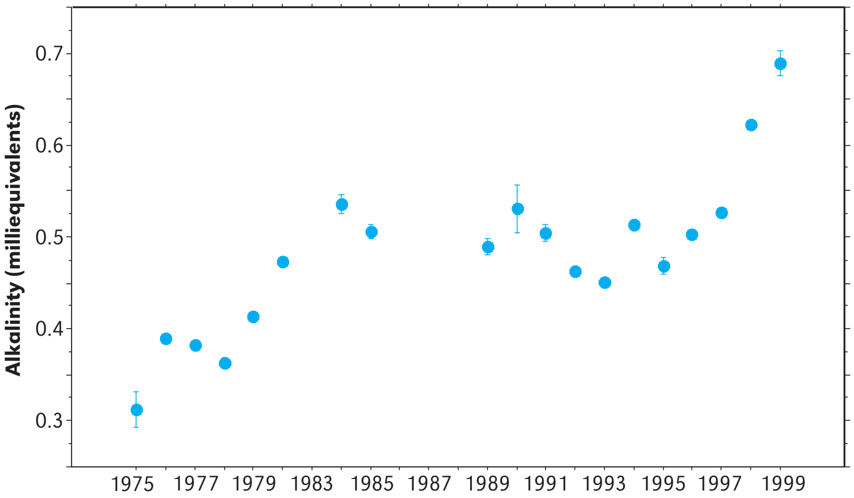


Figure 1-4. Progressive change in alkalinity of Toolik Lake, Alaska, from long-term, synergistic hydrology and hydrochemical measurements. Chemical changes may signal the warming of permafrost in response to global climate change (Neil Bettez, Arctic LTER database).

2

A Strategy for Detecting and Understanding Arctic Hydrological Change: Arctic-CHAMP

We recommend development of a pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) to provide the structure and framework for synthesis studies of the pan-arctic water cycle. Arctic-CHAMP would provide a focal point for cross-disciplinary research that focuses on the linkages between land, atmosphere, ocean, and biota.

The overall structure of Arctic-CHAMP is shown conceptually in Figures 2-1 and 2-2. It consists of three basic, interacting components:

1. compilation and evaluation of monitoring data on the hydrologic cycle,
2. field observations and focused process studies, and
3. simulation models operating over local to regional to pan-arctic domains.

We will focus on the individual contributions of these primary scientific elements but also discuss how they should be integrated for maximum benefit. The execution of Arctic-CHAMP, which requires a consideration of its organizational structure, specific program activities, and links to ongoing NSF, U.S., and international research programs, is detailed in Chapter 6.

Arctic-CHAMP Basic Long-Term Monitoring

We recommend that steps be taken immediately to reconstitute, sustain, and improve upon the basic hydrologic monitoring systems of the Arctic. The long-term observations necessary to understand the consequences of global change on the hydrosphere are currently

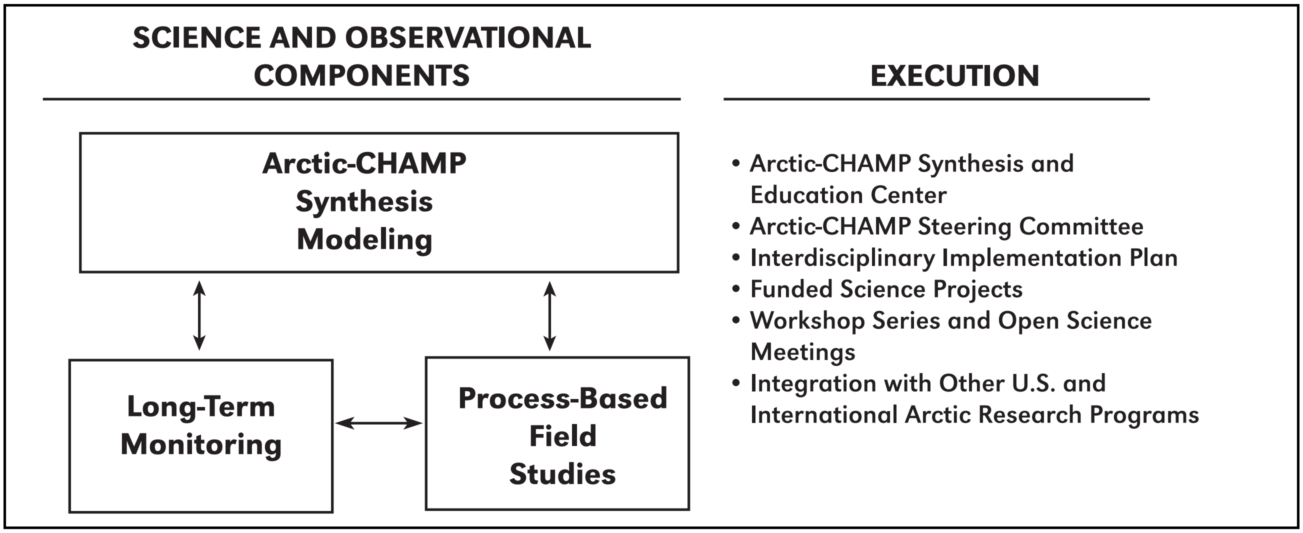


Figure 2-1. Overall framework of the Arctic Community-Wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP). The science and technical goals of the project are considered in Chapter 2. Execution of the program is described in Chapter 6.

unavailable. The Arctic is where we will best be able to measure the early signs of global change. A sustained commitment of resources will be necessary to develop the infrastructure necessary to capitalize on this unique scientific opportunity.

The value of documenting long-term changes in arctic temperature, precipitation, snow cover, sea ice, and storms has been demonstrated (Serreze et al. 2000). These progressive changes are occurring across the very region where general circulation models (GCMs) have predicted the earliest and largest greenhouse warming (Houghton et al. 1996, 2001) and where observed changes are consistent with predicted trends. Unfortunately, at precisely the time we need these records most, the quality and extent of arctic monitoring networks have diminished substantially (IAHS Ad Hoc Group on Global Water Data Sets 2001; Shiklomanov et al. in review) (Box 2-1).

The existing network of hydrometeorological stations devoted to long-term monitoring needs to be aggressively reconstructed and optimized in order to detect and accurately track the unique signature of global change on the Arctic. Consideration needs to be given to deploying instruments for observing the system as a whole. This is a fundamental goal of the new interagency Study of Environmental Arctic Change (SEARCH) Program (SEARCH SSC 2001), which goes well beyond hydrology per se. To support continued availability of hydrologically relevant monitoring data, we recommend the following steps, all of which require a commitment to free and open data exchange (Box 2-2):

1. ***Rescue Data:*** Critical data from past monitoring and measurement programs needs to be identified, recovered, and made available. Support for translation, documentation, accuracy checking, and conversion of paper archives to electronic media is needed. In vast areas of Eurasia, monitoring networks continue to deteriorate and every effort should be made to rescue critical data from these stations. Some of this effort (Holmes et al. 2000, Lammers et al. 2001; cf. National Snow and Ice Data Center) is underway, but much more needs to be done.

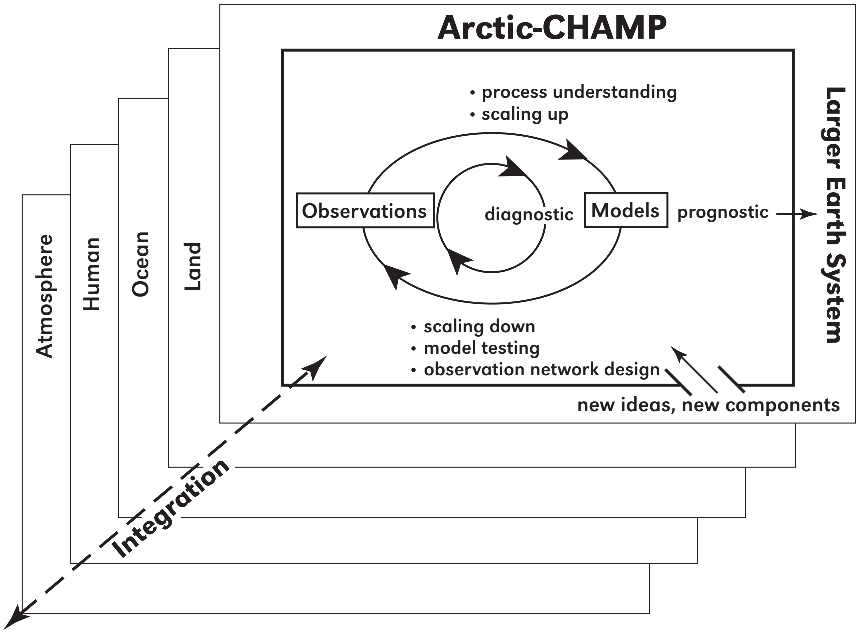


Figure 2-2. Overall conceptual framework of the pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP).

2. ***Sustain/Augment Observational Networks:*** Ground-based arctic hydrological and meteorological sites where long-term observations are most valuable need to be identified and steps taken to ensure that measurements will be continued at these sites. Threatened sites can be found not only in Eurasia but in North America as well. For example, atmospheric moisture fluxes determined from numerical weather prediction model reanalyses ultimately depend on the routine rawinsonde network which has been in decline since the early 1990s.

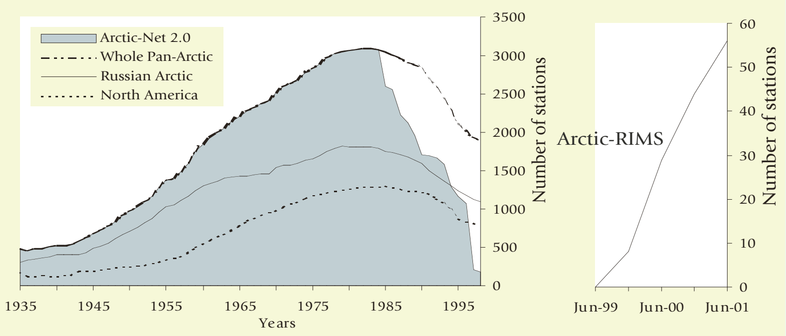
3. ***Improve Autonomous Instrumentation:*** Because much of the Arctic is remote and uninhabited, there is a pressing need for better and more reliable autonomous instrumentation for collecting hydrological and meteorological parameters. Critical improvements are needed in communications, power, and in the measurement of precipitation, notorious for gauge-related bias.

Box 2-1. The Deterioration of Arctic Hydrographic Monitoring Networks

Despite sensitivity of the pan-arctic region to global change and mounting evidence of its response expressed through the arctic water cycle, we see an increasing number of obstacles to the timely and broad distribution of *in situ* monitoring data. Precipitation data are threatened for several reasons. In spite of the universal importance and high value of accurate measurements of rain and snowfall, the number of measurement stations continues to decrease. The data that does exist is not always usable due to gauge undercatch that occurs (particularly for snow) in windy areas (Benson 1982, Goodison et al. 1998, Yang et al. 2000).

The situation has been particularly troublesome with respect to discharge data, which are viewed as a strategic information resource subject to formal and informal data policy restrictions and commercialized for cost-recovery (National Research Council 1999, IAHS Ad Hoc Committee on Global Data Sets 2001). Time series of available pan-arctic discharge monitoring station data sets is shown below (Lammers et al. 2001), and the problem is obvious. In the Russian Arctic, we have seen a 30% decline in operational capacity since 1990. Delays in data reduction and release, in many countries amounting to several years, greatly exacerbate the problem. Large quantities of otherwise reliable data exist in difficult-to-use paper formats, warehoused for years and in grave risk of damage. Canada has seen a 20% reduction in the number of discharge stations since 1990, many in the Arctic (B. Goodison, Environment Canada, Downsview ONT, personal communication, 2000). In Canada there has been a push to establish instrumented monitoring stations that are untended during the winter. Much data such as snow depths are now not collected and other data are compromised by instrument failure during winter. The U.S. also has lost river station time series, including the vital lowermost station on the Yukon River, which fortunately has just been reopened. Accurate water chemistry data over the pan-arctic are even more fragmentary (Holmes et al. 2000).

The situation is in stark contrast to the real-time availability of meteorological and oceanological data for weather forecasting. The mismatch between river discharge and meteorological data availability interferes with the timely identification and interpretation of a changing hydrology of the pan-arctic. A good example is the most recent estimate of present-day freshwater inflow to the Arctic Ocean, based on six-year-old observations (I. Shiklomanov et al. 2000). A temporally harmonized data set for pan-arctic hydrology and meteorology will be essential to the future monitoring of global change in the region.



Time series of station holdings from a pan-arctic hydrographic archive (R-ArcticNet) (Lammers et al. 2001) and an operational data bank (Arctic-RIMS). Both net declines in operating stations (lines) and multiyear delays in data access (unshaded area) are apparent in the panel on the left. Arctic-RIMS represents a concerted effort to obtain timely hydrographic records for a set of key stations (from Shiklomanov et al. in review).

Arctic-CHAMP Field-Based Process Studies

We recommend that a commitment be made toward establishing a core set of pan-arctic watershed study sites where a tightly integrated set of process-based measurements and monitoring can be systematically carried out over a long time frame. An interdisciplinary perspective is central to the success of these field studies.

There is a conspicuous lack of fully coordinated studies of hydrological processes in the Arctic. Decades-long watershed studies like Coweeta, Hubbard Brook, and H. J. Andrews have made major contributions toward our process-based understanding of temperate ecosystems and provide essential calibration and validation data to a wide spectrum of hydrological and hydrological-biogeochemical models. From these sites has emerged critical information on water cycle dynamics, for instance, how precipitation and evapotranspiration interact to regulate runoff throughout the year. Comparable facilities dedicated to integrated analyses of arctic hydrological processes must be established.

Box 2-2. Open Data Policy

The success of CHAMP will depend heavily on a policy of free and unrestricted data exchange. In light of the continued loss of hydrometeorological monitoring capacity (Box 2-1) this continues to be of critical importance. The arctic scientific community has only recently compiled an adequate historical archive of data sets that can be combined to detect systematic changes to the arctic system. When this has been done for the issue of change detection (Serreze et al. 2000), it has provided compelling evidence of major warming trends, atmospheric circulation changes, and a host of associated impacts. The NSF Arctic System Science Program has already invested heavily in community-wide databases by supporting the National Snow and Ice Data Center in Boulder, Colorado.

An Arctic-CHAMP Hydrometeorological Data Archive (HDA), representing an integrated community data resource, should be created as part of the overall CHAMP effort. HDA should serve as a repository not only for station-based measurements (such as meteorological and hydrological data) but also for second-generation data (gridded interpolations of point measurements and thematic interpretations of spatially distributed data sets) and model input and output files (such as associated with GCMs or regional climatic models). Each of these data sets should be organized in standard formatting, distributed through the Internet, and accompanied by appropriate metadata to explain the methodology used to create each data product.

Contributions of data to the archive should be an obligation of every scientist who receives funding under NSF ARCSS programs, and in particular Arctic-CHAMP. Charging a fee to use data or limiting access to that data places obstacles in the path of rapid scientific advancement (IAHS Ad Hoc Group on Global Water Data Sets 2001, Kanciruk 1997). Data should be freely distributed to anyone upon request. However, in keeping with the long-standing tradition in the NSF-funded geosciences, an exclusive right to data providers to first complete their analyses and publish those data as appropriate should be granted before release to the general community.

To fill current gaps in our process-based knowledge and to improve our capacity to simulate and predict arctic hydrologic and ecosystem change, research at these sites would comprise:

- experiments to uncover hydrologic mechanisms through the conjunction of fieldwork and modeling;
- measurements allowing comparative analyses with other watersheds; and
- research to improve the transferability of site-specific process studies and measurements to unmonitored sites, larger drainage basins, and the entire pan-arctic.

The coordinated set of activities would constitute hydrological as well as biogeochemical and biological measurements, including seldom-made winter observations (Table 2-1). Since permafrost is the single most dominant control on arctic terrestrial hydrological processes, it is important that the sites span a latitudinal gradient extending southward from the Arctic Ocean into the region of discontinuous permafrost. The sites must also encompass both tundra and boreal forest biomes because there is evidence that these ecosystems are changing rapidly and that the change is intimately linked to hydrology. As shrub invades tundra, or spruce follows shrubs, a variety of hydrologic consequences and feedbacks are operating, all of which impact humans and potentially the global system.

We recommend that a joint NSF working group consisting of researchers from LAII, OAII, HARC, PARCS, SIMS, and LTER be convened to study the costs and benefits of establishing and maintaining an integrated set of well-instrumented small arctic catchments. The group should advise on an optimal set of measurements that would support process understanding, process modeling, and pan-Arctic extrapolation, as well as on-site location to encompass the full range of landscapes typical of the pan-arctic land mass. The group should include observationalists, modelers, and researchers from Canada, Scandinavia, and Russia and international scientific programs so that the choice of sites augments existing networks and is of greatest value to modeling.

Arctic-CHAMP Synthesis Modeling

We recommend that an Arctic-CHAMP Integrated System Model (ARC-ISM) be developed. One way to promote synthesis in arctic hydrology is to integrate existing models and develop a simulation system that can provide a formal mechanism for mass and energy balance accounting, process-level testing, hypothesis generation, and pan-arctic application. ARC-ISM is intended to provide such a mechanism. It also provides a framework for integrating the long-term monitoring and process-based experimental elements of Arctic-CHAMP.

ARC-ISM (Figure 2-3) is an earth system model focused on the Arctic. It should treat in an integrated fashion the Arctic's climate, land surface hydrology, ocean, vegetation, biogeochemical, and human systems. Equally as important, it must be able to quantitatively articulate the pan-arctic's connection to the larger earth system, which will be critical for analyzing feedbacks in response to global change. Retrospective, contemporary, and future time frames need to be analyzed, with ARC-ISM cast as a *diagnostic* as well as *prognostic* modeling tool. ARC-ISM should be considered to be a numerical modeling *framework* serving as a flux coupler to which various component models (land, ocean,

Table 2-1. Examples of the coordinated set of measurements that might be made at an Arctic-CHAMP study site. Efforts should be made to expand the number of sites and the number of variables routinely observed.

Hydrological and Other Geophysical Measurements

- Precipitation Amount (Year Round)
- Evapotranspiration and Sublimation
- Solar Flux and Surface Energy Measurements
- Snow Pack
- Snow Redistribution
- Snow Melt
- Soil Thermal Properties and Their Variation
    - Temperature Profiles
    - Active Layer Depth
    - Permafrost Temperature
    - Thermal Conductivity
- Infiltration on Frozen and Unfrozen Soils
- Soil Moisture
- Runoff Flow Paths
- Stream and Large River Discharge
- High-Resolution and Accurate Digital Elevation Models

Biological and Biogeochemical Measurements

- Precipitation Chemistry
- Vegetation Surveys
- Soil Mapping
- Monitoring of Vegetation, Soil, and Groundwater Chemistry
- Stream and River Constituent Concentration
- Aquatic Ecosystem Surveys
- Isotope and Other Tracers for Discharge Entering Arctic Ocean

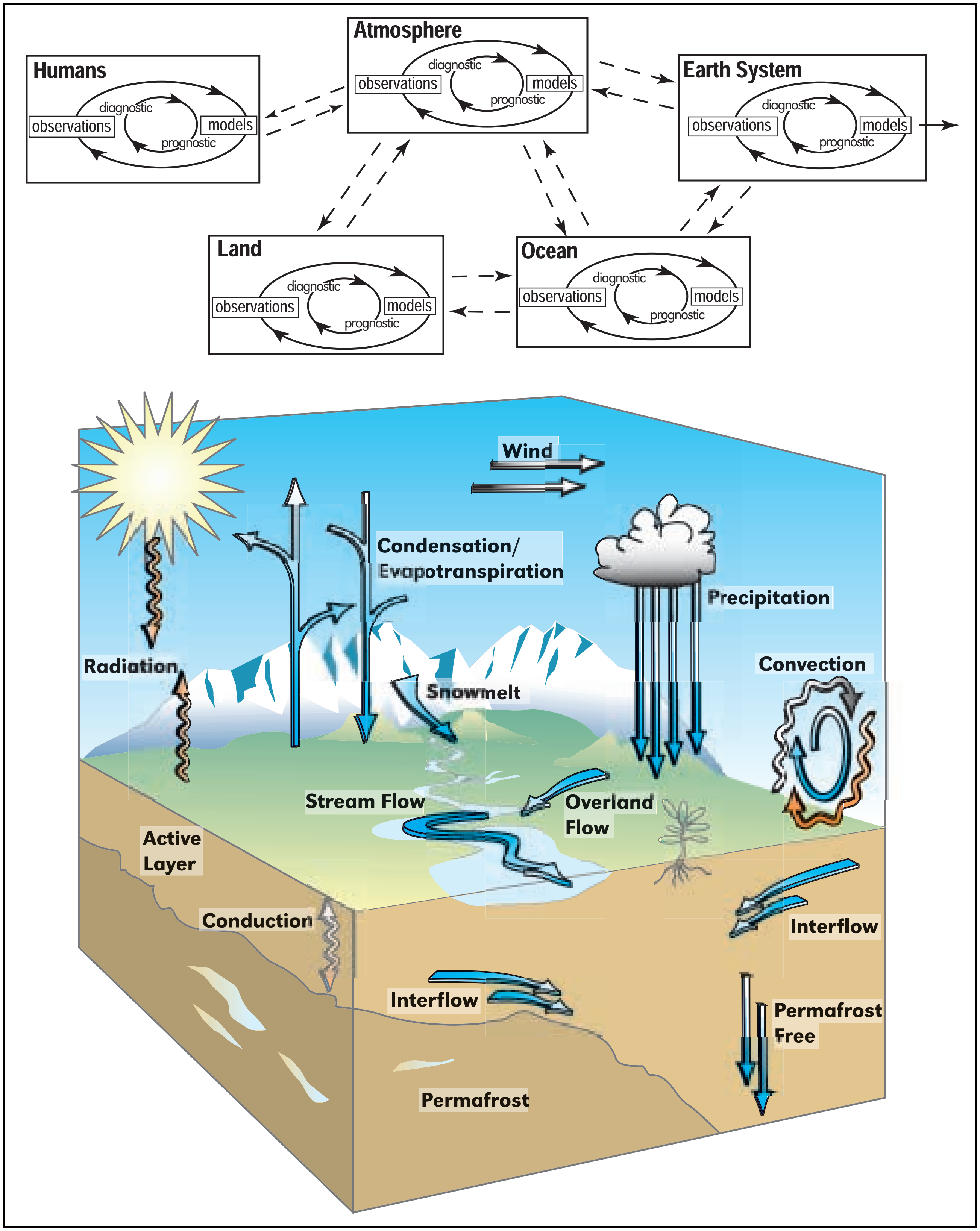


Figure 2-3. Major features of the Arctic-CHAMP Integrated System Model (ARC-ISM) showing (top) the overall conceptual domains of the model and (bottom) the land surface hydrological component in more detail. The land includes vegetation, soils, river corridors, wetlands, and aquatic ecosystems. Carbon, nutrient, and other constituent fluxes will be modeled in tandem with the simulated water cycle dynamics.

atmosphere) could be attached. This would allow for the necessary flexibility to make the overall modeling scheme accessible to the broadest user community. Success will require strict adherence to rules governing module coupling and documentation.

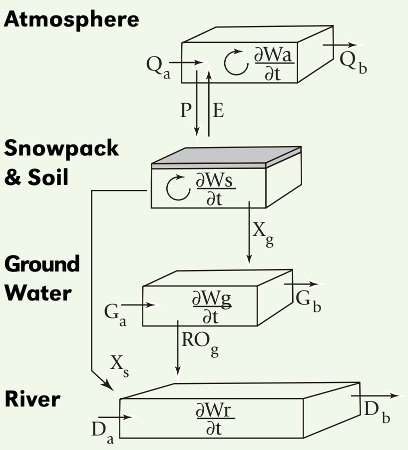
ARC-ISM in diagnostic mode should be used to analyze retrospective and near-real time water cycle dynamics, drawing on experience and techniques developed through state-of-the-art atmospheric modeling. These models include the current generation of General Circulation Models (GCMs) and Regional Climate Models (RCMs). "Reanalysis" efforts by the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) constitute a promising method for obtaining relevant fields for the pan-Arctic. Atmospheric transports of water vapor provide the fastest and most direct link between the pan-arctic and global climates and are therefore of great value in articulating the coupling of the Arctic to the earth system. Such models provide us with the necessary tools for analyzing this linkage and for quantitatively assessing changes to the pan-arctic water budget. An emphasis on improving the accuracy of such models is clearly warranted (e.g., Gutowski et al. 1997). Data assimilation for all key variables of the hydrologic cycle should also be fostered explicitly.

The diagnostic ARC-ISM can also offer an important resource in the design of optimal monitoring networks for hydrological variables. Precipitation, for example, remains one of the most crucial but difficult-to-estimate hydrologic measurements. Precipitation fields can be obtained through spatial interpolation techniques that produce high-resolution gridded data sets (e.g., Willmott and Rawlins 1999, Willmott and Matsuura 1995, Hutchinson 1998) based on station data, topography and/or existing climate information. The techniques are sensitive to station density, which is in decline over much of the Arctic. The diagnostic version of ARC-ISM could be used in numerical experiments to identify critical stations requiring formal protection and to formulate an optimal deployment strategy for new sites. Identification of the appropriate level of spatial and temporal detail necessary to capture the salient features of hydrological processes—working from the intensive field site models up to the domain of the pan-arctic—would be a major activity of the ARC-ISM modeling group.

An important opportunity presents itself to the arctic research community through a rapidly emerging suite of remote sensing data resources provided by U.S. and international space agencies. Given its pan-Arctic perspective, ARC-ISM could provide an important testbed for satellite sensors specifically targeted at the hydrology of high-latitude landscapes. Its initial use could be in testing data sets in existing remote sensing repositories (Alaska SAR Facility [http://www.asf.alaska edu], National Snow and Ice Data Center [http://nsidc.org]), which have not yet been adequately exploited for hydrological studies (Walsh et al. 2001). One particularly important data set for high-latitude runoff simulation would be an accurate and high-resolution digital elevation model (DEM), which has yet to be collected for the pan-Arctic despite major investments to obtain this information for other parts of the world (i.e., recent NASA Shuttle Radar Topography Mission). Space-borne sensors that show promise in delineating critical seasonal transitions in the arctic hydrologic cycle (McDonald et al. 1999, Running et al. 1999, Frolking et al. 1999, Kimball et al. 2001) could be investigated and rigorously tested in the context of ARC-ISM. It could also be used to create specific new sensor science requirements that could be acted upon in the design phase of these sensors (Cline et al. 1999).

ARC-ISM should also be configured to run in prognostic mode over the pan-Arctic. Current arctic regional climate models incorporate several interacting components of the hydrologic system, including atmosphere, ocean, land surface, and biosphere (e.g., Lynch et al. 2001, Wei et al. in review). These regional climate models operate at much higher spatial resolutions than global climate models, but their boundaries are provided by the coarse-scale GCMs into which they are nested. Such models may eventually provide detailed spatial descriptions of climate change scenarios. The models could thus be used to gauge the impacts of greenhouse warming on plant community structure or altered runoff generation and river discharge to the Arctic Ocean. Some specific applications of the ARC-ISM integrated modeling

Box 2-3. Arctic-CHAMP Framework Application: Atmosphere/Land Surface Hydrology Reanalysis



$$\frac{\partial Wa}{\partial t} = -\nabla\vec{Q} + E - P$$

$$\frac{\partial Ws}{\partial t} = P - E - X_g - X_s$$

$$\frac{\partial Wg}{\partial t} = -\nabla\vec{G} + X - RO_g$$

$$\frac{\partial Wr}{\partial t} = -\nabla\vec{D} + RO_g + X_s$$

Atmosphere

Observations	Processes
Water Vapor	Cloud Micro Physics
Aerosol Profiles	Boundary Layer Processes
Wind Profiles	Moisture Convergence
Temperature Profiles	Modulation/Influence by AO, NAO, ENSO, PNA
Cloud Cover	
Precipitation	
Evaporation	

Land

Observations	Processes
Precipitation	Infiltration
Evaporation	Snow Melt
Snow Cover	Freeze
Soil Moisture	Thaw
Permafrost	Thermokarsting
Discharge	Runoff ($X_s + RO_g$)

W_a = precipitable water (vertically integrated)

$\nabla\vec{Q}$ = horizontal water vapor flux divergence

E = evaporation + transpiration

P = precipitation

W_s = snowpack/soil water storage

X_g = excess water to groundwater pool

X_s = excess water to river/surface pools

W_g = groundwater storage

$\nabla\vec{G}$ = horizontal groundwater flux divergence

RO_g = runoff from groundwater

W_r = river water storage

$\nabla\vec{D}$ = horizontal discharge divergence

t = time

As the sophistication of atmospheric modeling has increased, it is now possible to begin quantifying a wide array of hydrologically relevant components of the overall climate system—for example, the troposphere, land surface, ocean, and stratosphere. New techniques for assimilating meteorological observations directly into Numerical Weather Prediction (NWP) models fosters the improvement of operational products as well as the reanalysis of long time series of historical archive data. These are important data sets because they provide us with the raw material for analyzing quasi-periodic phenomena such as ENSO, AO, and NAO. Working with U.S. (NCEP) and European (ECMWF) meteorological services, ARC-ISM researchers would be well positioned to develop an optimal land surface model for Arctic NWP. Improved representations of specific processes would include runoff generation at the surface and at depth, storage in the soil in liquid and solid forms, surface sublimation or evapotranspiration, surface storage in the form of snow, river routing, etc. When combined with atmospheric and oceanic models that contain an optimal representation of arctic physical processes (e.g., sea ice, arctic stratus, arctic haze, etc.), a reanalysis designed specifically for arctic hydrology could be realized. Hydrologic predictions constrained by all available observations would be obtained with high time resolution for a period of many years using an appropriate data assimilation scheme. Such a project would have to be a combined effort of the arctic hydrology community and experts in NWP. Improved reanalysis parameterizations have a major additional benefit: the enhancement of near-real-time, operational weather forecasts for the pan-arctic using versions of the same NWP models. An application of the equations shown here can be found in Box 2-4.

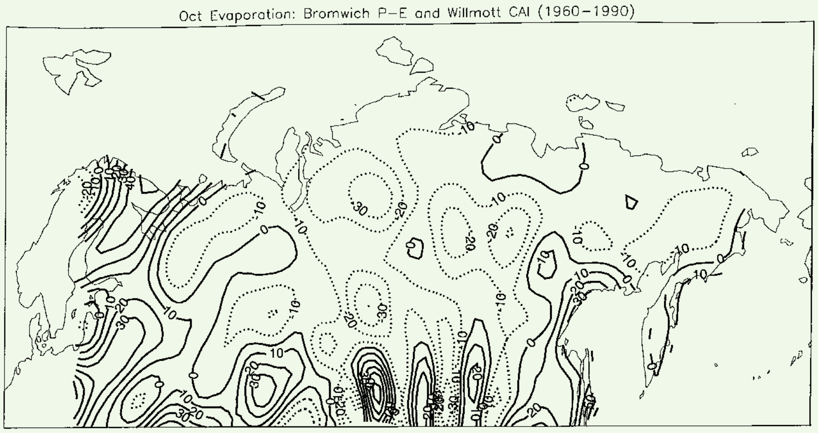
framework are given in Boxes 2-3 through 2-8.

Execution of Arctic-CHAMP

While each element of Arctic-CHAMP is important in its own right, we believe their integration will be the key to significant and rapid progress. To that end, Arctic-CHAMP has been structured to provide facilities and synthesis support activities linking the three components of the initiative—monitoring, process studies, and synthesis modeling. To afford pan-arctic integration, a multiscale approach will be fundamental, incorporating under a single framework broad-scale monitoring network data sets, site-specific hydrologic research, and simulation.

Successful synthesis will not be automatic, and the otherwise independent monitoring, field experimentation, and simulation components of Arctic-CHAMP will require a continual and concerted effort at integration. The management of the program will thus be a key to its success. The overall program goals can be achieved by incorporating guidance from a steering committee, providing support to targeted science and technology projects, entraining promising young investigators, funding expanded monitoring, coordinating with existing arctic research programs, and making a strategic investment in science infrastructure. These programmatic elements are detailed in Chapter 6.

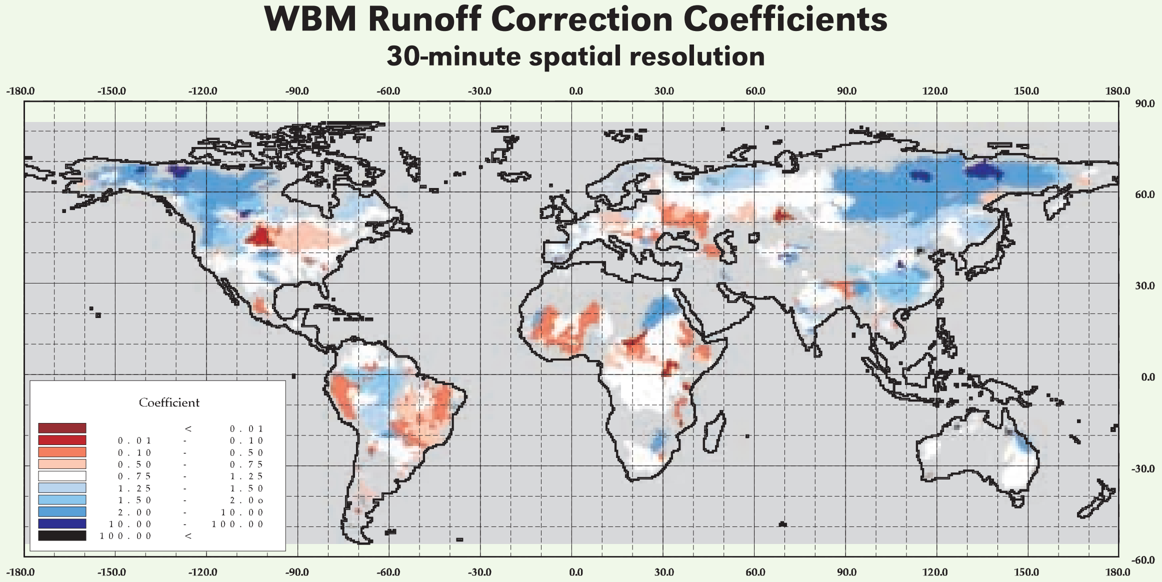
Box 2-4. Arctic-CHAMP Framework Application: Diagnosing the Performance of Model Outputs


Oct Evaporation: Bromwich P–E and Willmott CAI (1960–1990)

Computed evapotranspiration from the combination of aerological budgets from NWP reanalysis and an independent precipitation data set (Willmott and Matsuura 2000). Note the negative values, incongruent with our current understanding of system dynamics. The framework for combining such data sets is at the heart of the ARC-ISM algorithm and Arctic-CHAMP more generally.

In its diagnostic mode, Arctic-CHAMP should be designed to maximize our ability to judge the consistency among individual data sets, both against themselves and observational archives. Thus, Arctic-CHAMP would be a test bed for intercomparison studies using equations of the form shown in Box 2-3. An example would be testing for disparities among several existing precipitation data sets and the translation of these discrepancies into runoff uncertainty. In another example, preliminary assessment by M. Serreze (University of Colorado, Boulder, unpublished data) demonstrates that when NCEP atmospheric divergence fields and station-based, interpolated precipitation fields are blended to generate estimates of spatially varying evapotranspiration, these estimates give wholly unrealistic, large negative evapotranspiration values (see Figure). Ongoing work demonstrates that fields can be somewhat improved by accounting for gauge undercatch of solid precipitation (Serreze et al. in review). Such sensitivity tests allow the community to judge the degree to which observations of individual water cycle elements contribute uncertainty to the overall water budget closure across the pan-Arctic. Identification of such "weak links" is a necessary step in identifying fertile areas for future research.

Box 2-5. Arctic-CHAMP Framework Application: Design of Optimal Monitoring Networks



Potential bias in river basin precipitation as inferred from closure experiments on global water budgets. For much of the arctic drainage basin there are strong negative biases (blue color), which are likely associated with underestimates of regional precipitation (from Fekete et al. 1999).

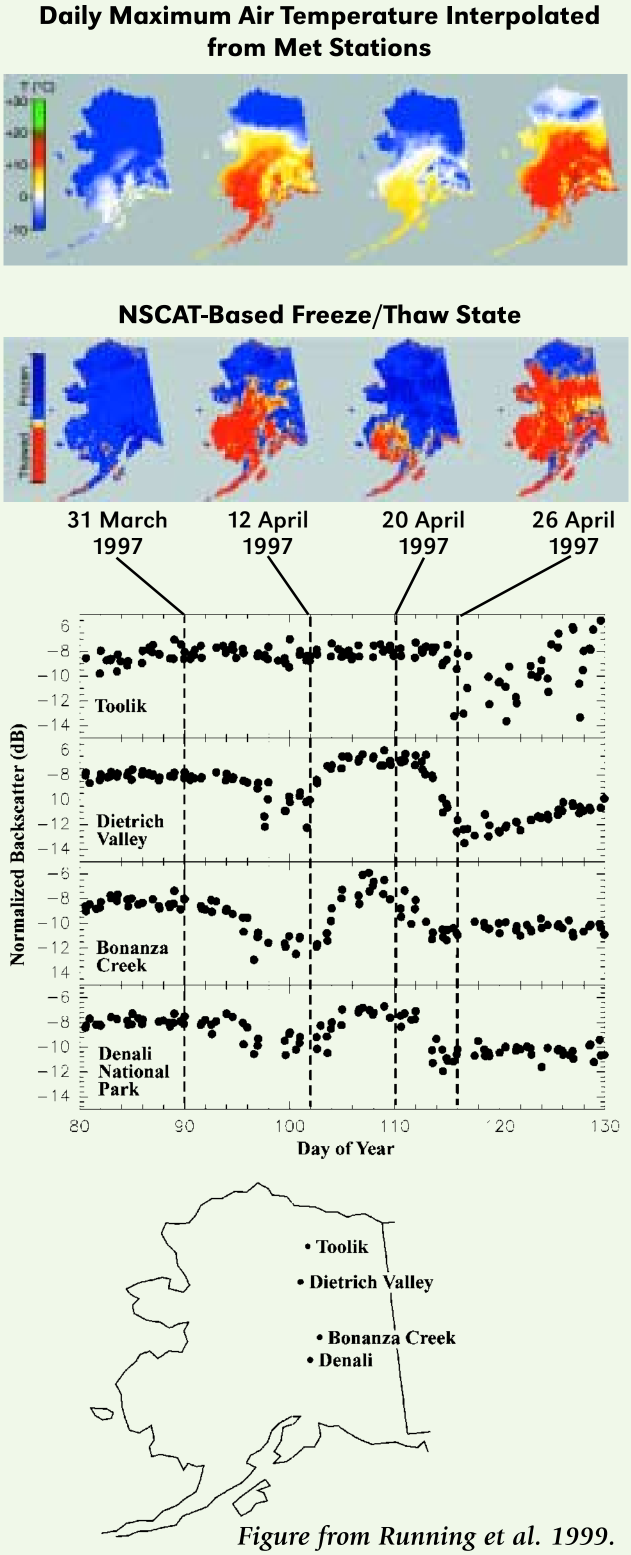
River discharge is one of the more accurate observations associated with the global hydrological cycle. However, real-time river discharge data has been underutilized within the ocean-atmosphere modeling community due to typical three-to-five-year delays in data posting (GRDC 1996), network closure, and data policy restrictions.

Recent work (Fekete et al. 1999) has demonstrated the capacity to identify possible sources of error in particular elements of the water cycle when judged objectively against the instrumental record. The figure above shows the spatial distribution of potential biases in precipitation when compared against observed discharge and a physically consistent water budget model. It is noteworthy that the Arctic, when analyzed from the standpoint of river discharge records over large river basins, shows sizable underestimation. This corroborates, from an independent perspective, the well-known problems with gauge catch and interpolation bias in both liquid and solid precipitation measurements in such harsh environments (Groisman 1991, Groisman et al. 2001, Willmott and Matsuura 1995).

The experiment shown in the figure indicates that by combining otherwise decoupled data sets and models, we can assess the degree of uncertainty and potential bias (see also Box 2-4). In addition, it lends hope that the synergy embodied in these data sets can yield a mutually consistent picture of water and energy budget closure. ARC-ISM should be used to optimize such an integration of data and model results and could beneficially be applied in the design of future monitoring systems for the pan-arctic system. These should be optimized to retrieve information of direct value to the scientific objectives of Arctic-CHAMP. However, of particular note would be the additional use of ARC-ISM derived products to help improve operational forecast and reanalysis products from weather prediction services. A coherent pan-arctic observational program in support of Arctic-CHAMP thus would provide an important framework for improving our capacity to monitor change over the Arctic and to interpret its impact.

Box 2-6. Remote Sensing Support for Pan-Arctic Synthesis

Comparison of maximum air temperature, interpolated from measurements acquired from 72 meteorological stations in Alaska with freeze/thaw index maps derived from two-day NASA Scatterometer (NSCAT) satellite sensor composite mosaics. NSCAT was extremely sensitive to the presence of unfrozen water on the surface of the snow or ground and is therefore a promising platform for determining hydrologic conditions over wide areas. The bottom four graphs show temporal series of NSCAT backscatter at four locations along a north-south transect extending (1) from Toolik Lake on the north slope of the Brooks Range, (2) to the Dietrich Valley, surrounding Coldfoot, Alaska, near the northern limit of the boreal forest, (3) through the Bonanza Creek Experimental Forest in the central interior, and (4) to Denali National Park in the Alaska Range. Each point on the four graphs represents mean NSCAT backscatter computed over a 50 km region centered at the respective ground location. The broken vertical lines mark the times initiating the two-day NSCAT composite mosaics. Remote sensing will provide critical observational support to Arctic-CHAMP synthesis studies. From the unique vantage point of space, satellite-based sensors constitute an important monitoring asset for constructing comprehensive views of the changing biogeophysical character of the entire pan-arctic domain (see Walsh et al. 2001). Use of such remote sensing data sets will be critical to observational support for pan-arctic synthesis studies as part of Arctic-CHAMP and to afford pan-arctic coverage.

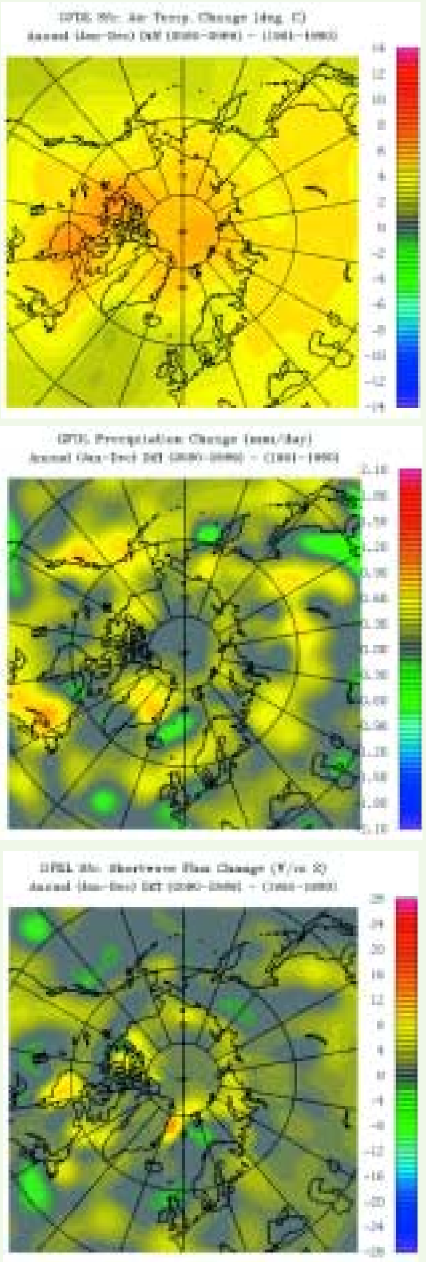


Daily Maximum Air Temperature Interpolated from Met Stations

NSCAT-Based Freeze/Thaw State

Figure from Running et al. 1999.

Box 2-7. Arctic-CHAMP Framework Application: Prognostic Simulation



The Arctic-CHAMP model can be used in a prognostic mode to produce high-resolution sets of scenarios on the potential future state of the pan-arctic system. The ARC-ISM model could easily be envisioned to represent a regional simulation nested within a larger earth system model, but with higher detail in its physical representation of land surface hydrology, ecosystem and vegetation state, coastal and Arctic Ocean, sea ice, and the dynamic atmosphere. The coupling has several advantages. It permits the full-system behavior to be assessed, as well as any subcomponents that would be the targets of more focused studies, thereby enabling feedbacks to be better elucidated. In addition, through scenario analysis it could be used to test for system sensitivities. And, using results derived from the error analysis developed under the diagnostic mode, ARC-ISM could be used to predict the impact of uncertainties in our understanding of possible future trajectories of environmental change.

Changes in annual mean surface air temperature (top), precipitation (center), and surface solar radiation (bottom) over the 100 years from 1961–1990 to 2061–2090, according to a greenhouse simulation by the GFDL coupled global climate model. Units are degrees C, mm per day, and Watts per square meter, respectively. Yellow and red denote increases; green and blue denote decreases, and gray denotes little or no change (IPCC Data Distribution Center, http://www.dkrz.de/ipcc/ddc/html/dkrzmain.html).

Box 2-8. Arctic-CHAMP Framework Application: Human Dimensions

The interactions between humans and the hydrological cycle in the Arctic are an integral part of the Arctic-CHAMP concept. Humans are responsible for damming rivers, deforestation, and agriculture, which alter the timing, amount, and quality of runoff to the ocean. Conversely, arctic hydrological conditions affect humans inhabiting the Arctic in many other ways (see Table 5-2). Ice and snow affect the everyday lives of arctic residents, including their commercial activities as well as traditional hunting and fishing. Permafrost changes affect the stability of engineering works such as roads, hospitals, schools, houses, pipelines, and industrial structures. Sea ice conditions affect both coastal hunters and commercial shipping along Alaska's arctic and Chukchi coasts, Canada's Northwest Passage, and the Northern Sea Route of Russia.

These issues have a fundamental geophysical underpinning which will be integrated within Arctic-CHAMP. The necessary links to these dynamics must be made by a consortium of physical and biological scientists and socioeconomic experts. Human dimension considerations have sometimes been treated merely as speculative or as anecdotal adjuncts to natural-science research. Arctic-CHAMP could serve as a vehicle for more empirical, observational research aimed at understanding the links between human systems variables and arctic hydrology. Documenting changes observed by indigenous populations would be especially important in this context, owing to the strong dependence of native residents on the arctic environment. Physical science and modeling work will seek to identify aspects of arctic hydrological systems that have varied substantially in the recent past, and/or appear likely to exhibit substantial change in the future. Researchers can then use this information as a starting point to systematically investigate the societal implications, including human responses to the hydrological variations that are already being observed.

A tundra pond was created among the Prudhoe Bay oil fields after a short gravel road was removed. Anthropogenic influences may have direct or indirect impacts on the hydrologic system (photo by L. Hinzman).

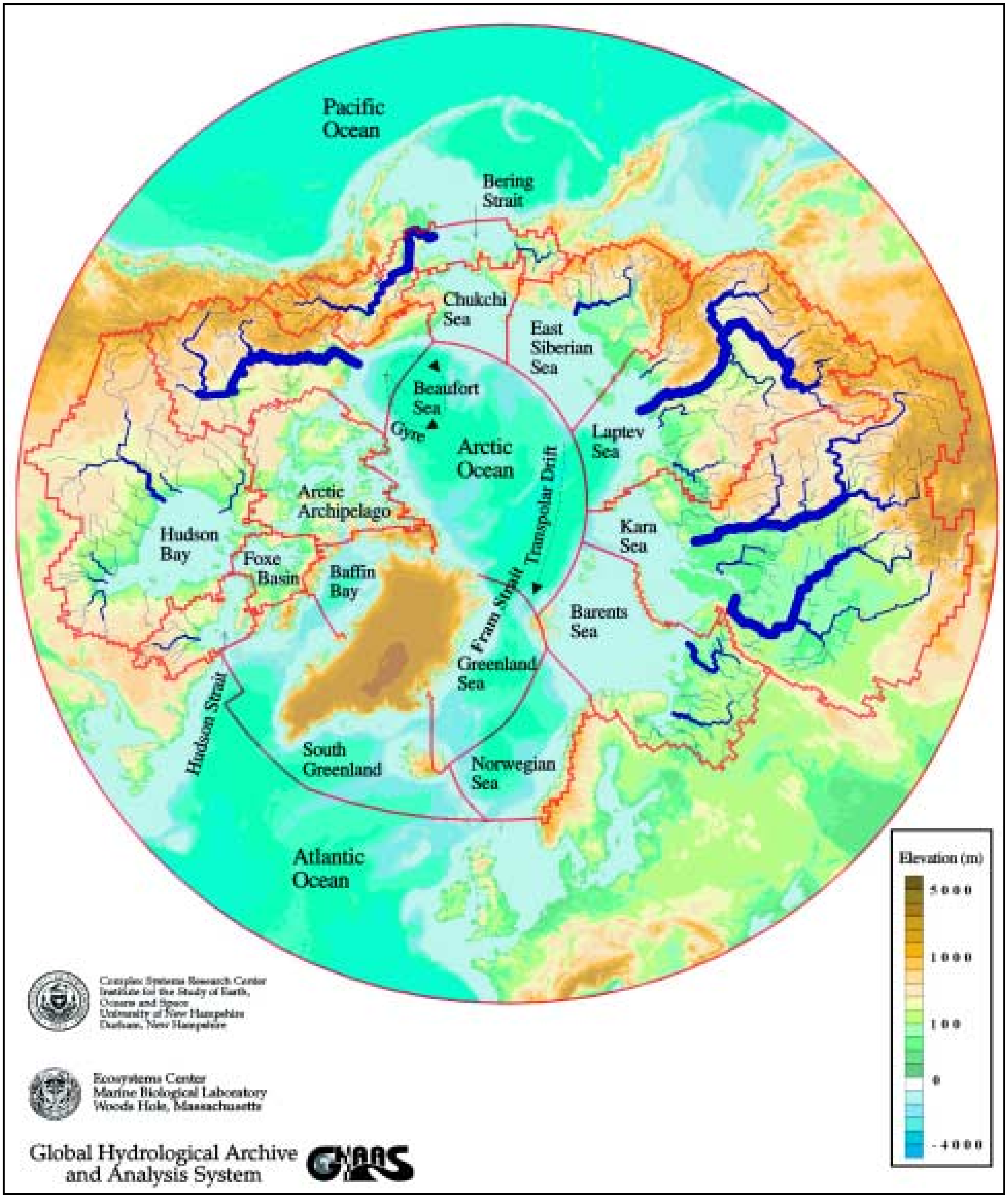


Figure 3-1. A view of the pan-arctic region, showing the contributing drainage basin of the Arctic Ocean and its numerous seas. Blue lines represent relative river discharge. The coupling of atmosphere-land-ocean is strong, and knowledge of the region's hydrologic cycle is central to our understanding of the sensitivity and reaction of the overall arctic system to global change (from Forman et al. 2000).

3

Role and Importance of Water in the Arctic System

The Integrated Water Cycle of the Pan-Arctic

The hydrologic cycle figures prominently in the dynamics of energy and constituent exchange among the land, atmosphere, and oceanic components of the arctic and larger earth system (Figures 1-1, 1-3). The coupled arctic land-atmosphere-ocean system is complex, and without a comprehensive understanding of the integrated water cycle, we cannot hope to understand the changing arctic environment or the global consequences of this change.

For this assessment, we maintain a broad conceptual and geographic definition of the pan-arctic region. Geographically, the pan-Arctic is a more or less well-bounded segment of the larger earth system (Figure 3-1). The land mass draining into the Arctic Ocean and discharging freshwater through the Bering Strait can be easily identified (Lammers et al. 2001, Prowse and Flegg 2000), together with the ocean fluxes from the Pacific and exchanges with the North Atlantic. In addition, the arctic circumpolar circulation, including the Polar Front, is a fundamental feature of the earth's climate system that can be clearly tracked. We use this domain as our organizing framework to examine how the arctic hydrologic cycle interacts with the coupled land-ocean-atmosphere system.

In this section, we first review the multiple roles that water plays in each of the major domains of the pan-arctic system, namely land, atmosphere, and oceans. We then turn to the question of how the arctic water cycle functions in the larger arctic and earth systems.

Land

Water responds strongly to the extreme contrast between summer and winter conditions over the arctic land mass (Figure 3-2; Box 3-1). During the thaw season water runs off, transporting mass, energy, and momentum through watersheds and ultimately to the Arctic Ocean in ways similar to lower latitude river systems. But unlike watersheds in more temperate regions, snowmelt runoff produces normally a single, sharp peak flow event for the year. Water cycling through arctic landscapes provides the moisture plants need; is a source of vapor to the atmosphere; and through runoff, transports sediment and other constituents to the ocean. Surface flow, ponding, and freeze-thaw are the primary drivers of erosion and geomorphic change because thermal, along with mechanical factors, regulate the runoff and erosion processes. In sharp contrast, during the long frozen season water itself becomes the land surface in the form of lake ice, river ice, and most importantly, snow, which radically increases the land surface albedo (reflectivity) and reduces the solar energy absorbed, but at the same time provides a blanket of high-quality insulation that reduces ground heat losses.

Seasonal delays in the storage and release of snowpack are extremely important in regulating connections between the land surface and overlying atmosphere and highlight the complexities associated with the hydrological cycle's role inside the arctic system. The nine-month-long winter, with strong negative energy balance, thus serves as an important storehouse for water that is later destined to become runoff or precipitation through local recycling. The seasonal storage of snowpack represents water imported into the Arctic from great distances, and thus emphasizes an important link of the pan-Arctic to the larger climate system. Large river basins then transport this water equally great distances with eventual delivery to the coastal seas of the Arctic Ocean.

Figure 3-2. Example of a permafrost dominated landscape with sharp contrasts in the state of water cycling between the long winter and short summer (photographs courtesy of J. Holmgren, L. Hinzman, Y. Kodama).

A unique and important feature of arctic hydrology associated with the long, cold winter is the presence of permafrost and a summer active layer (the layer of soil above the permafrost that thaws each summer). Permafrost limits the amount of subsurface water storage and infiltration that can occur, leading to wet soils and ponded surface waters, unusual for a region with such limited precipitation. Active layer thickness and permafrost conditions are largely controlled by surface heat fluxes, coupling the hydrology to the surface energy balance so closely that they cannot be quantified separately. In summer, solar heating leads to rapid thawing of the active layer, while in winter, a delicate balance between the thermal insulation of the snow cover and its high albedo controls the rate and severity of freezing. Since large stocks of organic carbon are currently sequestered in permafrost, changes in the coupled thermal-hydrologic system have the potential for creating important feedbacks to the global carbon cycle.

Box 3-1. Unique Water Cycling in the Arctic

Terrestrial hydrology in the Arctic differs substantially from hydrology at lower latitudes in several important ways:

- great contrasts occur between summer (liquid water) and winter (solid water) hydrological states;
- extensive and long-lasting snow cover insulates the ground and reflects solar energy;
- permafrost and an active layer control soil moisture and fluvial erosion, and intimately link hydrology to the thermal balance of the soil;
- vegetation cover, closely coupled to soil moisture and the active layer, affects surface energy exchange—causing feedbacks to hydrologic and thermal systems; and
- freeze-thaw controls hydrological cycling and thus the abrupt seasonal changes in available nutrients to arctic plants, flux of biogenic gases to the atmosphere, and export of carbon and nutrients to rivers and seas.

Strong seasonality characterizes arctic hydrology (Figure 3-2). During the long winter, precipitation is stockpiled as snow, while lakes and rivers are frozen. Winter radiation balance is dominated by longwave losses to space. The short, intense spring thaw starts a period of more vigorous transport. Spring runoff produces the highest discharge values of the year (Grabs et al. 2000) and water begins to infiltrate the still-frozen ground (Kane and Stein 1983). As spring warms into summer, surface soil layers thaw, providing water and nutrients to plants. Evaporative rates increase, and runoff increases substantially—often tenfold or more.

Large changes in surface energy balance follow this annual cycle. During winter up to 85% of incoming shortwave solar radiation is reflected (Geiger 1957, Barry 1996), but sensible heat loss from the ground is reduced by continuous snow cover, an excellent thermal insulator (Mellor 1964, Sturm et al. 1997). In summer, vegetation type and its insulation capacity affect the ground's thermal state (Eugster et al. 1997, McFadden et al. 1998). Annual energy balance determines the temperature of permafrost as well as the thickness of the active layer. These in turn interact with surface and subsurface water flows.

Much of the Arctic resembles a desert, in terms of annual precipitation—less than 200mm per year in some regions (Korzoun et al. 1978). But this is a desert that can look like a bog, with wet soils and lush green vegetation. Permafrost prevents surface water from draining, supporting the formation of hydrophilic ecosystems. Should the climate warm or the surface be disturbed, however, warm permafrost can degrade. Thermokarsts (Figure 5-2) form as ice-rich soils or massive ice thaw. Then, surface soils subside, creating large depressions or ponds. If thawing continues, taliks (layers of unfrozen soil above permafrost) persist through the year. These taliks allow soils to drain and set in motion dramatic changes in vegetation.

Atmosphere

The atmosphere carries water evaporated from the oceans and precipitates it in the form of rain and snow onto arctic land areas, oceans, and sea ice. Much of the water and energy comes from lower latitudes in the form of water vapor, making the atmosphere an important conduit connecting the rest of the globe to the Arctic. In addition, this poleward atmospheric transport carries with it contaminants and other chemical species into an otherwise "pristine" environment. Annual precipitation falling onto arctic river basins is modest in comparison to that in lower latitudes because cold air masses are unable to hold much moisture. During the winter, precipitation is almost entirely in the form of snow and the wintertime precipitation rate is about half that in summer, which together with modest rates of evaporation and sublimation, leads to a limited local recycling of water. Although snowfall can occur on any day of the year, summer precipitation varies from primarily rain in the south to mixed rain and snow in the north. Maximum precipitation rates occur in the short summer season, often in conjunction with thunderstorm clouds. High evaporation rates in summer lead to predominantly localized recycling of water. The freeze-thaw cycle, affecting the seasonal accumulation of snowpack, snowmelt, and the mobilization of water through soil and vegetation during the summer, is a dominant feature of the hydrology of the Arctic.

Ocean

The timing and distribution of freshwater inflow critically affects Arctic Ocean circulation as well as water and energy exchanges with the atmosphere. Principal freshwater sources are in the form of discharge delivered by north-flowing rivers. Warm, salty Atlantic water enters the Arctic Ocean through the eastern side of Fram Strait and across the Barents Sea shelf (Figure 3-1). Less saline Pacific water enters through the Bering Strait. These fresh and saltwater sources, combined with sea ice freezing and melting and wind-driven circulation, produce an outflow through the western part of Fram Strait and the Canadian Archipelago that includes nearly fresh sea ice, cold surface water of relatively low salinity, and deeper water masses with salinities close to that of the Atlantic inflow.

The freshwater input is important to Arctic Ocean dynamics by contributing to the formation of the cold halocline layer, a water mass with a strong salinity gradient and near freezing temperatures, lying between the surface mixed layer and deeper, warm, salty Atlantic water. The estuarine and shelf zones between fresh river and Arctic Ocean waters have a particularly important role to play in these dynamics and may be especially sensitive to future change (MacDonald 2000). The maintenance of the cold halocline is important to the thermodynamics of the ocean basin. The temperature is so cold that it provides little heat to the mixed layer and ice, and the strong stratification of the cold halocline inhibits turbulent mixing of heat upward to the ice from the warmer Atlantic water below.

The freshwater output from the Arctic Ocean, in the form of sea ice and reduced salinity sea water, arguably has a large effect on the global ocean because it increases stratification in the Nordic and Labrador seas, reducing the deep convective overturning and thereby weakening the thermohaline circulation of the North Atlantic (Carmack 2000). In addition to affecting the thermohaline circulation for the whole earth, this change in the condition of the North Atlantic may directly feedback on the arctic freshwater cycle by changing the flux of heat and moisture through the atmosphere.

Importance of Arctic Hydrology to the Arctic System

Over the annual cycle, the terrestrial water cycle embodies a complex series of processes that regulate evaporation, changes in moisture storage, and runoff. Precipitation and evaporation serve as the critical links between the atmospheric and terrestrial segments of the hydrologic cycle. Land surface hydrologic budgets can be defined by the changes in total water storage (i.e., in soils, ground, and surface waters) which in turn equal the sum of time-varying precipitation, evaporation, and net runoff. The seasonality of frozen versus unfrozen landscapes is the definitive characteristic of arctic hydrological systems. Snowmelt typically generates the bulk of seasonal excess water and must be routed through soils and groundwater or overland into stream channels (Figure 3-3). In permafrost-dominated areas, the freezing and thawing of frozen soil is critical to the timing of plant growth and evaporation, infiltration, and runoff as well as the presence or absence of wetlands (Figure 3-4). These processes have been observed, but quantifying them over many pan-

Figure 3-3. Snowmelt is usually the dominant hydrologic event of the year in watersheds dominated by snow and ice. Monitoring snowmelt and the resultant runoff is essential to quantify the annual water balance in arctic and subarctic watersheds (photo by L. Hinzman).

arctic hydrological regimes in order to compute water budgets remains both an open area of research and a significant monitoring challenge.

The delivery of freshwater from the continental land mass is of special importance to the Arctic Ocean since it contains only 1% of the world's ocean water, yet receives 11% of world river runoff (Shiklomanov et al. 2000). The Arctic Ocean is the most river-influenced and landlocked of all oceans and is the only ocean with a contributing land area greater than its surface area (Ivanov 1976; Vörösmarty et al. 2000). Annual freshwater inflow contributes as much as 10% of the freshwater in the upper 100 meters of the water column for the entire Arctic Ocean (Barry and Serreze 2000). Approximately three-quarters of Arctic Ocean riverine freshwater input derives from the Eurasian portion of the Arctic Ocean watershed, and three rivers (Yenisei, Lena, Ob) are responsible for approximately 70% of this contribution (Carmack 1990, Gordeev et al. 1996). This water exerts a tremendous influence on the Arctic Ocean and especially on the Eurasian shelf seas (the Barents, Kara, Laptev, and East Siberian). Salinity distribution and sea ice formation are affected by continental runoff. As mentioned before, the cumulative impact of changes in freshwater flux to the Arctic Ocean may exert significant control over global ocean circulation by affecting the volume of North Atlantic Deep Water formation (Aagaard and Carmack 1989, WMO/World Climate Research Program 1994, Broecker 1997).

River inputs of water and constituents influence delta, estuarine, and near-shore ecosystems that have historically provided the basis for subsistence of northern Eurasian human populations. Climate change during the transition from the Pleistocene to the Holocene was accompanied by major shifts from utilization of terrestrial foods to use of riverine and coastal marine resources including fishes and mammals (Makeyev et al. 1993).

Importance of the Arctic to the Earth System

From a large body of GCM experiments, the Arctic is thought to be particularly sensitive to global climate change (Manabe et al. 1991, Manabe and Stouffer 1995, Houghton et al. 1996, 2001; Watson et al. 1998). Manabe et al. (1991) show that under a representative global warming scenario, temperature increases will be amplified in the Arctic, and the upper Arctic Ocean salinity will decrease due to enhanced precipitation at high latitudes. Analysis of a broad suite of archived hydrometeorological data sets further supports this view and suggests the presence of a global warming signal across the region (Serreze et al. 2000). Preliminary assessments for some regions of the Arctic show that recent changes in winter temperature and mean annual precipitation have affected local runoff conditions and river discharge to the Arctic Ocean (Lammers et al. 2001, A. Shiklomanov 1994, I. Shiklomanov 1997, Georgievsky et al. 1996). At the same time teleconnections have been established between El Niño Southern Oscillation (ENSO) events and climate anomalies in parts of the arctic drainage system (Brown and Goodison 1996, Shabbar et al. 1997).

Key indicators of global change thus involve major components of the high-latitude water cycle, and the reciprocal response of the Arctic—beyond its land-based hydrology—must be considered. For

Figure 3-4. Arctic wetlands depend on the presence of permafrost (photo by L. Hinzman).

example, the Arctic Ocean's stratification and ice cover provide a control on the surface heat and mass budgets of the north polar region, and thereby on the global heat sink (e.g., Manabe et al. 1991). If the distribution of sea ice—a significant stock of arctic freshwater—were substantially different from that of the present, then the altered surface fluxes would affect both the atmosphere and the ocean and would likely have significant consequences for regional and global climate. Also, the export of low-salinity waters, whether liquid or in the form of desalinated sea ice, has the potential to influence the overturning cell of the global ocean through control of convection in the subpolar gyres, which in turn feed the North Atlantic (Aagaard and Carmack 1989). Recent suggestions that North Atlantic and Eurasian climate variability may be predictable on decadal time scales (Griffies and Bryan 1997) rest in part on the variability of such upstream forcing in the Greenland Sea (Delworth et al. 1997).

Central Question: What Are the Major Features and Natural Variability of the Pan-Arctic Water Balance?

Key Gaps in Current Understanding and Needed Studies:

- Fluxes throughout the water cycle (atmospheric vapor transport precipitation, evaporation, soil water, runoff)
- Arctic atmospheric teleconnections to the larger climate system
- Role of seasonal snowpack and permafrost water storages
- Runoff generation and pathways
- Continental discharge and connections to sea ice and deep ocean convection

On the atmospheric side, results of Thompson and Wallace (1998) and others show that the atmospheric circulation of the Northern Hemisphere changes as part of a pole-centered pattern, termed the Arctic Oscillation (AO). Recent modeling studies suggest the AO is a fundamental mode of atmospheric change and that the positive trend seen in recent decades may be symptomatic of the greenhouse effect (Fyfe et al. 1999, Shindell et al. 1999).

Consideration of the coupled set of atmosphere-ocean interactions is thus absolutely essential to our understanding of the ultimate impact that arctic environmental changes have on the earth system. The hydrological cycle will figure prominently in any such analysis.

4

Unprecedented Change to Arctic Hydrological Systems

Change is an inherent property of the Arctic, with the paleoclimatic record providing ample evidence of the enormous changes experienced by the region since the last glacial maximum (Mayewski et al. 1994, Alverson, Oldfield, and Bradley 2000). The system has alternately experienced extensive and thick ice sheets, the blockage of northward flowing rivers, exposed coastal shelf regions, giant catastrophic floods, and most recently the complex signature of human-induced climate change. High-resolution paleo-records indicate that arctic climate can move rapidly from one regime to another, resulting in the anomalous persistence of warm temperatures, shifts in seasonality, extreme events, and changes in ocean circulation (e.g., Bond et al. 1999, Douglas et al. 1994). These and many other paleoclimate studies provide an understanding of arctic hydrologic variability and are needed to place the recent observations of Arctic system change into appropriate context (Stein 1998). Although changes to many environmental variables have occurred previously throughout geologic time, the rate of changes observed within the last few decades to century are quite likely unprecedented and indeed have evoked a sense of urgency within the community (Overpeck et al. 1997, Overpeck 1996, SEARCH SSC 2001, Serreze et al. 2000).

The multiagency SEARCH Science Plan (SEARCH SSC, 2001) provides an in-depth analysis of the spatial and temporal extent of recent changes to the arctic system. Many significant changes are observable from what is admittedly an incomplete and in many cases fragmentary record. The review given below focuses on the arctic system as well, but highlights those changes related specifically to the arctic water cycle.

Changes to the Land-Based Hydrologic Cycle

A wide range of changes in terrestrial arctic hydrology has been detected, and many of these changes started, or accelerated, in the mid-1970s. The arctic hydrologic system is particularly sensitive to changes in the magnitude and timing of rain and snowfall, freeze-up and thaw, and the intensity and seasonality of storm activity that reflect changes in large-scale atmospheric circulation rather than simple responses to temperature increases. Although historical changes in these fields are poorly known and characterized by enormous spatial and temporal variability, observations suggest that the arctic hydrologic system may be entering a state that is unprecedented, at least over a historical timeframe (Serreze et al. 2000, Lammers et al. 2001).

Integrated measures of hydrological status, such as glacier mass balance studies that record both summer and winter precipitation, indicate that over the last 30 years, smaller glaciers in the Arctic have experienced decidedly negative mass balances (Dyurgerov and

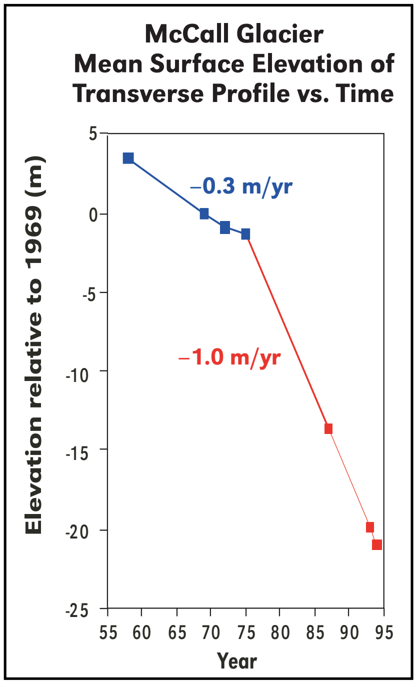


Figure 4-1. The McCall Glacier in the Romanzof Mountains of Arctic Alaska has been losing mass since measurements began in 1957, with accelerated losses over the last two decades (Rabus et al. 1995).

Meier, 1997). The 1957 to 1995 record for McCall Glacier in arctic Alaska (Figure 4-1) shows that the mass balance has not only been negative, but the rate of downwasting has increased dramatically since 1976 (Rabus et al. 1995). The Greenland Ice Sheet has also increased in melt area throughout the 1980s (Abdalati and Steffen 1997), and the associated reduction in volume is about equal to those of all the smaller glacier systems in the Arctic (Dyurgerov and Meier 1997).

Observed responses of arctic river systems to changes in temperature and precipitation reflect a complex set of spatial patterns, including a mean delay of nine days for freeze-up and a ten-day earlier ice breakup date for lakes and rivers, comparing conditions 150 years ago to today (Figure 4-2; Magnuson et al. 2000). Trend analysis of river outflow has been inconclusive. Shiklomanov et al. (2000) suggest very little change in mean annual discharge for large rivers over the last several decades, whereas Semiletov et al. (2000) document increases for several Eurasian rivers. Changes in the seasonal pattern of discharge in many Arctic rivers have occurred (Savelieva et al. 2000), but these changes are challenging to detect because of large natural variations. Changes in the base flow, such as the increases in the Yenisei River between 1936 and 1995 (Figure 4-3) (Yang et al. in review), are more distinct and thought to reflect increased groundwater infiltration coupled to reductions in permafrost and an increase in active layer thickness due to warmer temperatures (Figure 4-4). A recent analysis of discharge records from several hundred stations distributed across the pan-Arctic (Lammers et al. 2001) indicates there has been an increase in winter flow in several Siberian river basins during the 1980s. Such hydrologic changes can impact stream habitat, increase icing, and elevate the export of sediment and solutes to the ocean.

Changes to the Atmosphere

Within the atmosphere, evidence of unprecedented change is documented in the instrumental record of precipitation and temperature as well as in changes in synoptic scale circulation and variability. The paleo perspective extends the relatively short instrumental

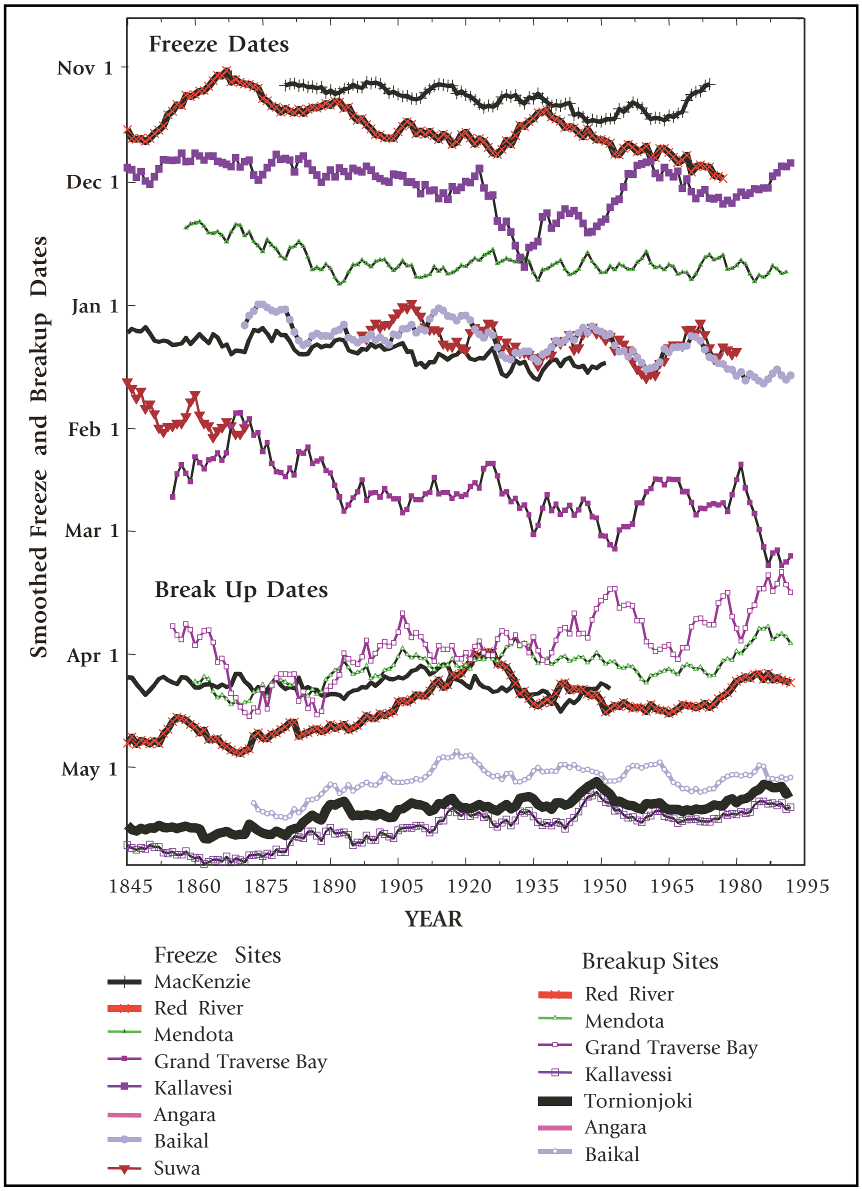


Figure 4-2. With increasing temperature, there have been noticeable changes in the dates of freeze up and ice breakup in many lakes and rivers of the Arctic. The average change over the 150-year period was nearly nine days later for freeze up dates and almost 10 days earlier for ice breakup dates of rivers and lakes in the Northern Hemisphere (Magnuson et al. 2000).

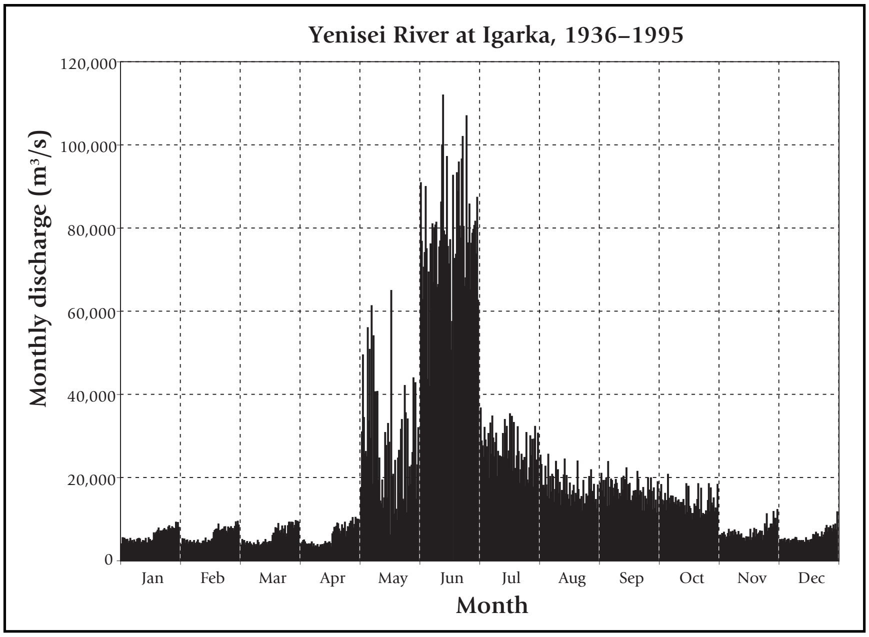


Figure 4-3. The base flow (non-surface runoff) of the Yenisei River increased markedly over the period from 1936 to 1995. For each month the plot shows the average conditions for each sequential year. This change is postulated to arise from increased groundwater infiltration coupled with permafrost degradation, which itself is a response to climate warming (Yang et al., in review). The construction of large artificial impoundments may also contribute to these changes.

Figure 4-4. Springs represent an important connection between groundwater and surface water, often forming at the permafrost boundary. Presence of well-developed minerotrophic vegetation indicates the spring has existed for many years. As permafrost degrades, the connections between groundwater and surface water increase, allowing springs to form or in some cases ponds to shrink (photo by L. Hinzman).

period and thus provides a more complete context for interpreting recent hydrologic variability and change. Overpeck et al. (1997) used a multiproxy regional synthesis to determine that arctic summer air temperatures of the 20th century have been the highest in the last 400 years, despite showing both positive and negative shorter term temperature trends. One warm period began in the 1920s and extended to the late 1940s; a second, still underway, started in the 1970s (Figure 4-5). The instrumental record of change in the Arctic indicates that high northern latitudes have increased in mean annual temperature by ~1°C, with the largest increase in winter temperatures (~2°C), whereas summer temperatures increased by ~0.5°C (Lugina 1999, Lugina et al. 2001). Serreze et al. (2000) confirm that temperature changes are spatially complex, with warming in northern Eurasia and western North America but cooling in eastern Canada and southern Greenland (Figure 4-6).

Instrumental precipitation records document a significant increase over northern Eurasia (Groisman 1991) over the last 50 years across northern North America (Groisman and Easterling 1994), whereas in eastern Russia over the same period there has been a decrease in summer precipitation (Sun and Groisman 2000). This decrease in eastern Russia over the last 50 years has been accompanied by a replacement of stratiform clouds with convective clouds. Overall, across much of Russia there has been an increase in convective cloudiness associated with an increase in the number of days with heavy precipitation (Sun et al. 2001).

The primary modes and variability of the North Atlantic Oscillation (NAO), and the closely related Arctic Oscillation (AO), determine interannual precipitation variations over Eurasia and eastern North America whereas western North America responds to variability in the North Pacific Ocean. Consistent with intensification of the NAO/AO over the last two decades, winter precipitation amounts and surface air temperatures have been increasing in northern Eurasia, decreasing in southern Eurasia, and decreasing in northeastern Canada in response to enhanced storm activity in northern latitudes (Serreze et al. 2000). Over the same period that winter precipitation has increased, there has been a dramatic decline in northern hemisphere snow cover (Robinson 1999) (Figure 4-7). Eurasian snow cover extent has decreased over the past 20 years (primarily in the spring and summer; Groisman et al. 1994). The same is true for Alaska where during the past 50 years a general retreat of spring snow cover was reported (Groisman et al. 2001). Most of this retreat has occurred during the past two decades, resulting in an earlier onset of spring by approximately two weeks.

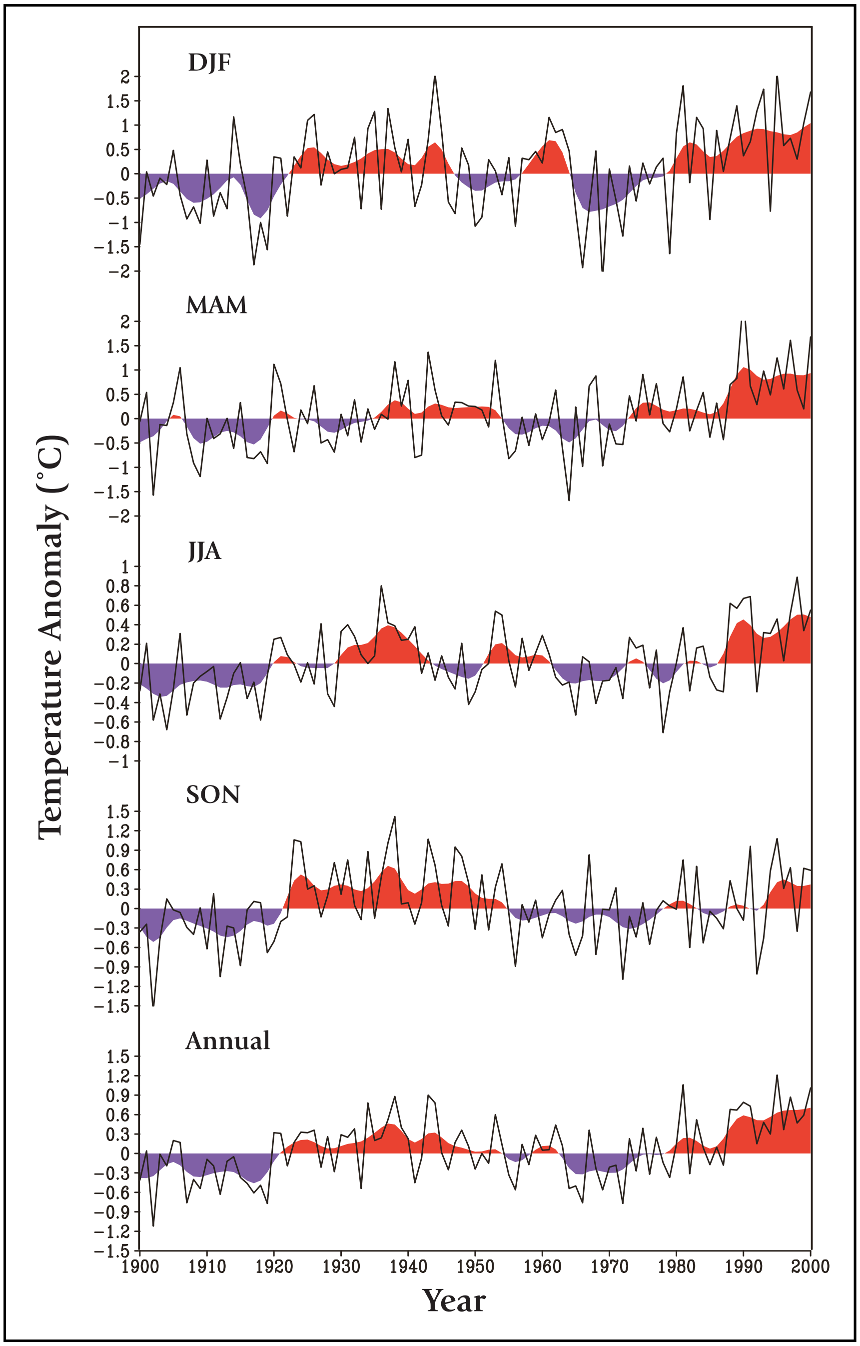
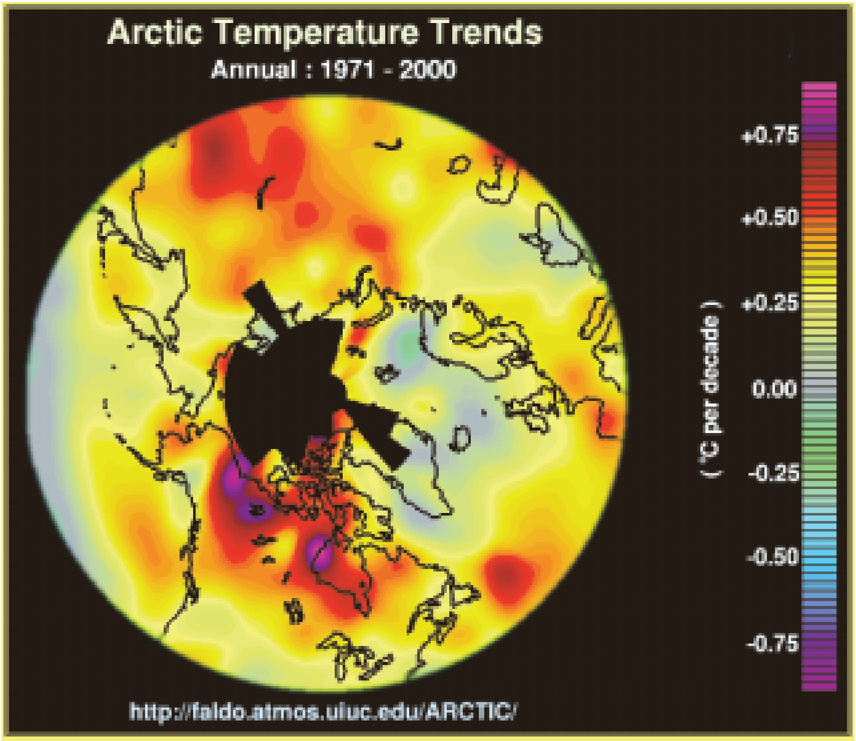


Figure 4-5. Time series of temperature anomalies for the 20th century for the Northern Hemisphere from 55° to 85° N (based on update to Eischeid et al. 1995).

These climate trends are consistent with greenhouse warming, however, uncertainty remains whether these phenomena reflect natural climate variability, anthropogenic forced (i.e., "global warming") or a combination. Changes in rainfall, snowfall, and the recycling of water back to the atmosphere through evaporation and sublimation are difficult to assess from the instrumental record because the network of stations is sparse and data collection difficult (Black 1954; Woo et al. 1983; Yang et al. 1999, 2001). Summer precipitation trends, determined by computing precipitation (P) minus evaporation (E) from numerical weather prediction model reanalysis (Walsh et al. 1994, Serreze et al. 1995, Cullather et al. 2000), reveal little systematic change over the past 30 years. Site-specific studies often yield less ambiguous results. In locations where direct land-



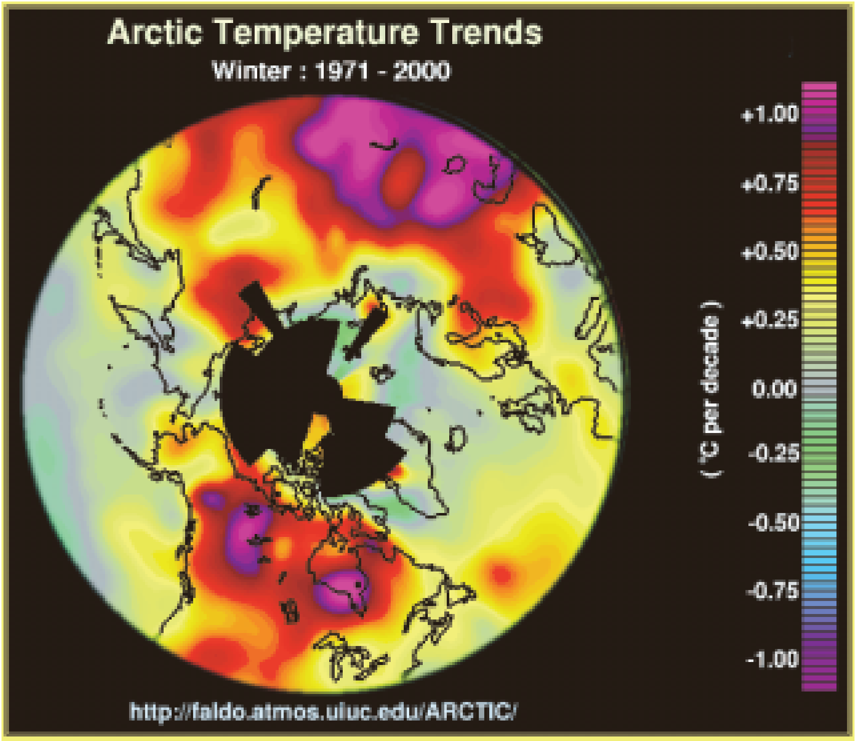


Figure 4-6. The geography of recent circumarctic temperature change. Updated from Chapman and Walsh (1993).

based measurements have been available (Oechel et al. 2000), an observed trend toward increasing summer precipitation (1960 to 1998) has been offset by increasing air temperature and evapotranspiration, resulting in a net gain of water vapor to the atmosphere and drying of the soil (Figure 4-8).

Although pan-arctic data sets of critical hydroclimatic variables can be assembled at relatively high resolutions using state-of-the-art interpolation and gridding techniques (Price et al. 2000, Willmott and Rawlins 1999), accuracy is limited by a deteriorating network of ground-based monitoring stations. Intercomparison tests (Rawlins 2000) suggest that not only are new techniques still

Figure 4-7. Understanding the processes controlling the variability of snowpack properties and snow cover distribution are critically important to understanding the current hydrologic regime and in predicting potential responses to climate change (photo by L. Hinzman).

necessary to narrow the substantial gaps in our detection of climate warming but a substantial upgrading of station holdings remains critical (Figure 4-9).

The Changing Arctic Ocean and its Regional Seas

Recent hydrologically related changes within the Arctic Ocean system include increased salinity in the central region, shrinking of the cold halocline layer, and decreased surface salinity off of western North America (SEARCH SSC, 2001). Specific hydrological observations include changes in ice drift pattern, decreased sea ice extent, and decreased sea ice thickness. Arctic sea ice extent decreased by 2.9 +/- 0.4% per decade over the last 30 years (Cavalieri et al. 1997) and analyses of passive microwave time series from satellites indicate that ice reductions have been accompanied by an increased length of ice melt season (Smith 1998). Arctic sea ice thickness measured by U.S. Navy submarines over the last 20 years record an average 43% reduction in thickness for the central Arctic Ocean (Rothrock et al. 1999). The yearly average pressure maps indicate a shift in the

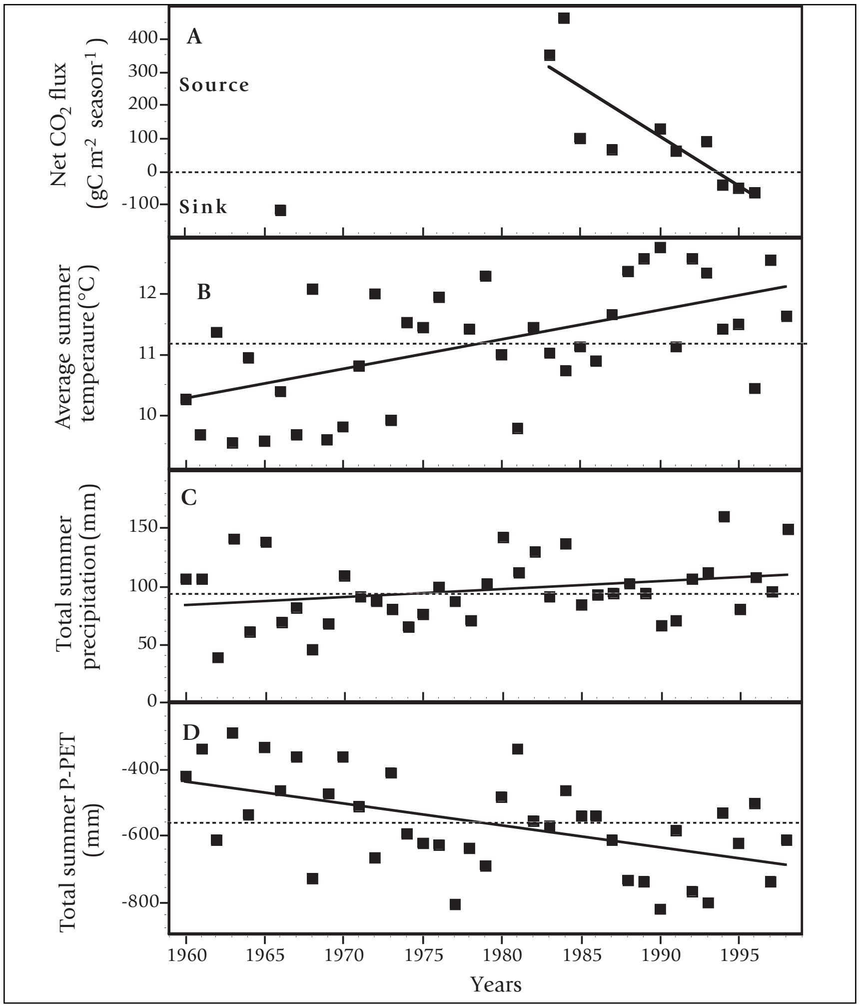


Figure 4-8. Changes in precipitation (P), potential evapotranspiration (PET), and their difference, a measure of net water available for soil water recharge and runoff. These data represent measurements made at four sites in northern Alaska. A net change in CO_2 flux is also tabulated as terrestrial primary productivity and ecosystem respiration are linked closely to moisture availability at these sites during the growing season (Oechel et al. 2000).

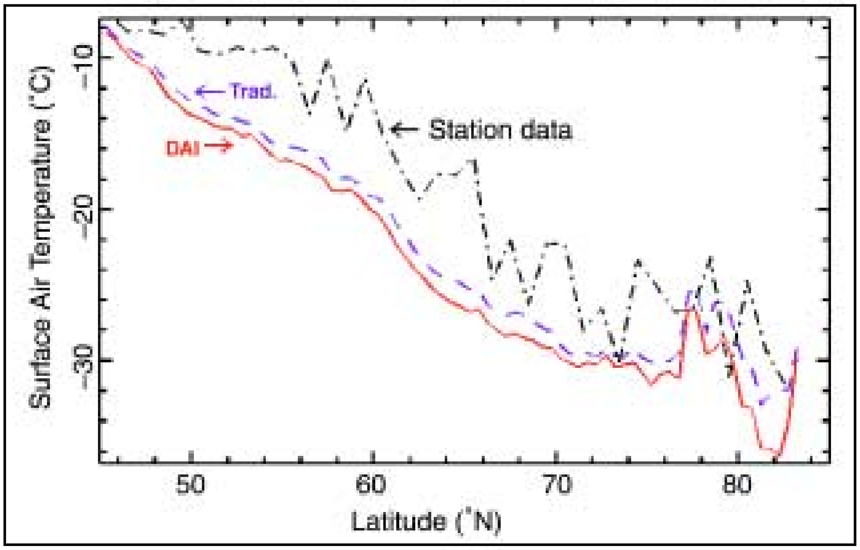
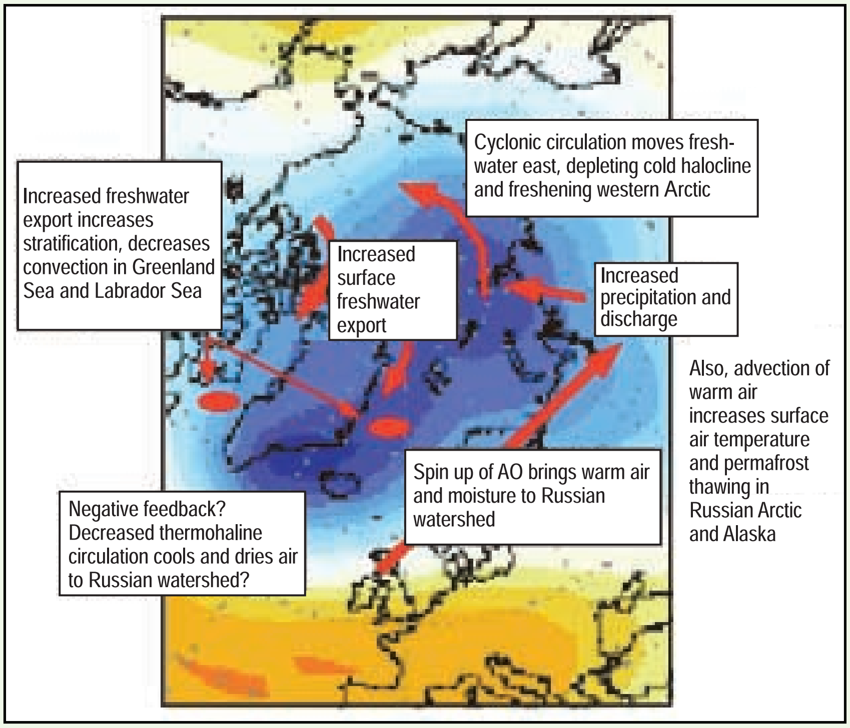


Figure 4-9. Impact of interpolation technique on the resulting bias in pan-arctic temperature climatologies. Latitudinally averaged (over 30′ latitude bands) mean surface temperature for winter is shown for traditional spherical interpolation versus Digital topography-Aided Interpolation (DAI) (Rawlins 2000). This graphic highlights the need to address systematic errors in our monitoring of hydrologically relevant variables across the pan-Arctic.

Box 4-1. The Arctic Oscillation and Hypothesized Connections to the Water Cycle



Based on extensive oceanographic observation, critical changes in the Arctic Ocean and changes to the land-based hydrologic cycle are hypothesized to relate closely to the onset of the Arctic Oscillation (AO) (Thompson and Wallace 1998). The working hypothesis is that as the AO index rises, the strength of the polar vortex increases, and the surface pressure in the Arctic Basin decreases, weakening the Beaufort high (Walsh et al. 1996). This applies positive vorticity to the sea ice and ocean circulation (Proshutinsky and Johnson 1997), resulting in reduced convergence in the Beaufort Gyre. This in turn results in more open water, greater radiative heat input, increased summer melt, and decreased Beaufort Sea surface salinity (McPhee et al. 1998). The change in circulation may also account for the decreased ice cover on the Siberian shelves (Maslanik et al. 1996). Increasing surface air temperatures are also thought to influence land-based freeze-thaw with potential acceleration of the terrestrial water cycle.

Steele and Boyd (1998) argue that the change in circulation reroutes Siberian river runoff to the east rather than allowing it to mix with Atlantic water, cool, and move cross-shelf to form cold halocline water. It is thereby responsible for thinning the cold halocline layer. The shift of Siberian runoff to the east may also be in part responsible for the freshening of the upper layers of the Beaufort Sea (McPhee et al. 1998, Macdonald et al. 1999). The increased cyclonic vorticity added to the Arctic Ocean may also act to draw surface water from the lower salinity, western region of the basin and increase the amount of fresh surface water flowing out through Fram Strait. This could increase stratification in the Greenland Sea and contribute to the weakened deep convection observed there in recent years (Aagaard et al. 1991, Schlosser et al. 1991).

An intriguing possibility is that reduced thermohaline circulation imposes a negative feedback on this system by causing less northward ocean heat flux into the Nordic seas and thereby cooling northern Europe and Russia, with important consequences for terrestrial ecosystems and human society.

These complex interconnections argue strongly for synthesis studies of the entire coupled arctic system. Integrated monitoring and simulation—at the heart of the overall Arctic-CHAMP initiative—will be essential to future progress in understanding these geophysical processes.

position of the Beaufort high, usually centered over 180° longitude before 1988–1989, to a more western position and weakening thereafter. These pressure anomalies are linked to changes in ocean circulation patterns and therefore the distribution of sea ice, terrestrially derived runoff, and salinity.

Collectively these changes represent some of the most compelling lines of evidence for arctic environmental change and suggest a substantial reorganization of the Arctic Ocean system, with important implications for ice cover, the ice-albedo feedback, and the terrestrial water cycle. These changes also highlight the integrative nature of the hydrologic cycle, linking land, atmosphere, and ocean. Box 4-1 describes some of the hypothesized links between the Arctic Ocean and freshwater dynamics. The full impact of the unfolding changes to the Arctic Ocean hydrologic system remains unknown, but the dramatic changes evident in numerous paleoclimate records underscore the importance of understanding both the magnitude and consequences of contemporary hydrological changes across this climatically sensitive region (Stein 2000).

Central Question: Are the Observed Changes in Arctic Hydrology Part of the Natural Variability or Are They Related Uniquely to Human-forced Global Warming?

Key Gaps in Current Understanding and Needed Studies:
- Design and implementation of long-term, coherent observational programs for water-related variables over land, atmosphere, ocean, and cryosphere
- Historical and paleo studies to establish benchmarks by which contemporary change can be measured
- Quantify the underlying processes controlling the natural variability and the observed unprecedented changes
- Studies that identify the causal agents of observed changes to arctic hydrosystems
- Trend analysis for early detection of global climate change

5

Impacts and Feedbacks Associated with Arctic Hydrological Change

Alteration of land surface hydrology in the Arctic imposes both direct and indirect effects on "downstream" components of the arctic system. Important direct impacts are conveyed on terrestrial ecosystems and human society. Indirect effects constitute feedbacks through which hydrological changes in turn cause changes to atmosphere and ocean dynamics. We treat two broad classes of feedback in this chapter, one involving the physics and biology of the Arctic and another considering human dynamics.

Direct Impacts on Ecosystems

Recent hydrological changes impact permafrost structure and stability, the distribution of arctic vegetation, and soil processes including CO_2 flux (Table 5-1). Data from an extensive set of boreholes indicate that permafrost temperatures have warmed 2 to 4°C across the broad region of Northern Alaska during the last century (Lachenbruch and Marshall 1986). Farther south in regions of discontinuous permafrost, 1 to 1.5°C of warming has been observed over the last 20 years (Osterkamp and Romanovsky 1999). In some places, the warming is sufficient to thaw the permafrost, resulting in significant landscape changes as massive buried ice melts. Where the thawed ground sinks below the water table, new swamps are created (Figure 5-1). In upland areas, drainage can be enhanced, converting wetlands to a drier ecosystem (Figure 5-2). Drier soils no longer support the plant and animal communities formerly adapted to live there—one of the many challenges to arctic ecosystems posed by climate change (Krajick 2001).

Figure 5-1. The hydrologic consequences of climate warming are very much site dependent. The Tanana Flats (Lat. 64°40′ Long. 147°50′) is an area of ice-rich permafrost and upwelling groundwater. As the permafrost degrades with climate warming, the surface collapses, and areas that were once birch and black spruce forests become flooded and are replaced by fens and bogs (photo from Jorgenson et al. 2000).

Recently observed changes in temperature, soil moisture, snow cover, and precipitation have resulted in spatially and temporally rich shifts in vegetation. Mosses and other tundra species insulate the ground and reduce active layer thickness (Luthin and Guymon 1974). When disturbed by fire or a warming climate, this ground cover is replaced by shrubs or even trees that change the thermal regime (Brown and Grave 1979). Local tree lines have been advancing in some places. Field studies have demonstrated a transition in land surface cover from graminoid-dominated to shrub-dominated tundra (Chapin et al. 1995, Henry and Molau 1997, Jones et al. 1997, Walker et al. 1999, Silapiswan in press), which could have important consequences for snow accumulation and winter biogeochemical processes (McFadden et al. 2001, Sturm et al. 2001, Liston et al. in press). Satellite remote sensing of NDVI (Normalized Difference Vegetation Index) records an increase in arctic plant growth and growing season between 1981 and 1991 that is consistent with an increase in shrubs (Myneni et al. 1997). A major challenge will be to monitor the progression of successional changes and their impact on seasonal evapotranspiration and runoff (Shiklomanov and Krestovsky 1988, Eugster et al. 1997, McFadden et al. 1998, Chapin et al. 2000), especially since vegetation changes occur on decadal time scales that are long relative to observational records, and thus difficult to detect. Box 5-1 schematically summarizes a few of the ways in which biotic and abiotic systems might respond to climate change.

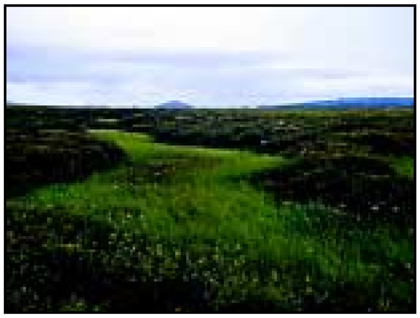


Figure 5-2. Thermokarst formation near Council, Alaska, has resulted in variable impacts to the local hydrologic regime. New riparian channels form as ice-rich permafrost degrades. As drainage improves in adjacent tussock tundra, soils become somewhat drier and the proportions of shrubs increase (photo courtesy of L. Hinzman).

Figure 5-3. Waterfowl that migrate to the Arctic each year depend on tundra ponds. Ice-rich permafrost prevents percolation of surface water to groundwater and maintains these ponds despite relatively low rates of precipitation (photo by L. Hinzman).

The arctic terrestrial system plays an important role in global carbon dynamics and may possibly be one of the so-called "missing sinks" needed to balance the atmospheric carbon budget (Tans et al. 1990, Ciais et al. 1995, Schimel 1995). Changes in arctic air temperatures and precipitation impacting soil moisture and snow cover have had an important effect on the efflux of CO_2 from the land, with global-scale climate implications. In recent years there has been a shift in parts of the Arctic from a net annual sink to a net source of carbon (Oechel et al. 2000). During the growing season the system continues to take up carbon (Figure 4-8), but this uptake is more than balanced by winter losses (Jones et al. 1997, Fahnestock et al. 1998, 1999, Vourlitis et al. 1997, 1999, Oechel et al. 1997, Zimov et al. 1993a, b).

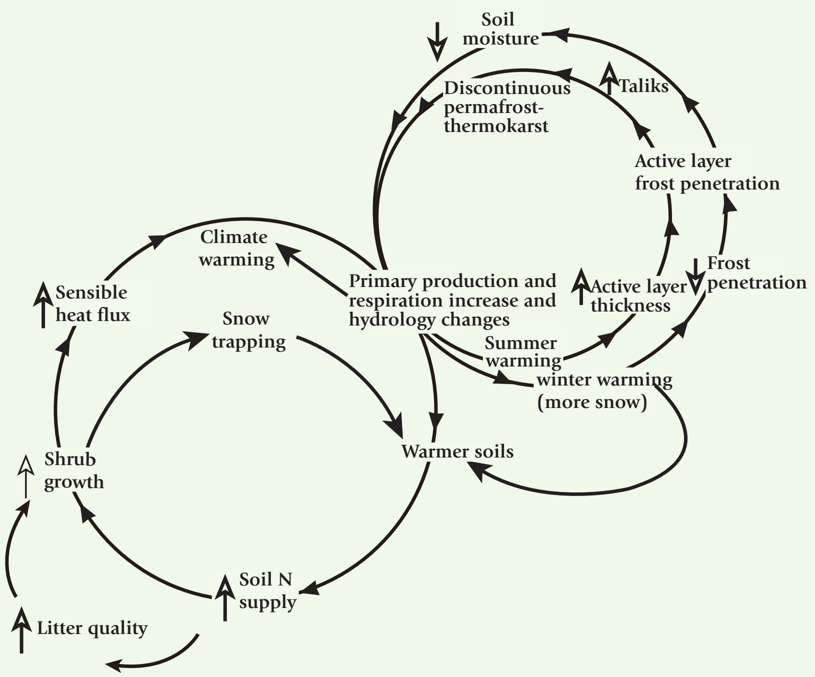
Whether the arctic land surface is a "missing sink" or not, the efflux and sequestration of carbon in arctic soils is intimately linked with hydrology. Soil moisture determines the rate of organic matter decomposition, with cold, wet soils generally limiting the decomposition process (Oberbauer et al. 1989). At the same time, much of the plant growth in the Arctic is nitrogen-limited (Chapin et al. 1995). Warming and drying not only promotes greater carbon efflux through decomposition (Oechel et al. 2000), but also increases nitrogen mineralization, promoting a shift in plant community composition toward more productive functional groups

(Chapin et al. 1995). The whole ecosystem response is complicated and still under investigation (Shaver et al. 2000), but the role of water, particularly in the form of soil moisture, is well established as critical to carbon cycling in the Arctic.

Arctic animals have adapted to their particular niche, and changes in the environment will influence all creatures. Terrestrial herbivores must be able to graze beneath the winter snowpack. Midwinter warming or rain events can introduce ice layers that prevent caribou and musk oxen from cratering the ice-encrusted snow. Similarly, such ice layers can prevent adequate wind pumping of fresh air to small rodents living under the snow. The circumpolar arctic serves as a breeding ground for dozens of species of waterfowl and other birds (Figure 5-3), and the condition of the arctic environment determines the size of populations that migrate to more temperate winter ranges. The timing of their migrations and very existence is strongly affected by local hydrological conditions. Water conveys obvious controls on aquatic habitat. Recent work in the Kuparuk River in Alaska shows an additional, close linkage between fish production and river discharge (Figure 5-4).

Marine life in the Arctic is conditioned by physical factors including circulation, temperature, salinity, and ice. Changes in these factors inevitably affect marine ecosystems. For example, cold low-salinity surface water anomalies originating in the Arctic can reduce vertical mixing, negatively affecting

Box 5-1. Postulated Land Surface Hydrology Responses to Greenhouse Warming



The hydrologic response of the arctic land surface to changing climate is dynamically coupled to the region's surface energy balance, thermal regime, and ecology. The coupling between hydrology and ecology takes place primarily through changes in the active layer of the permafrost. One likely consequence of climate warming will be that soil conditions will improve for shrubs, creating both winter (snow holding) and summer (increased nitrogen mineralization) conditions more favorable to shrub growth and dispersion (Sturm et al. 2001). Changes in land surface cover will change the energy partitioning and carbon cycling, thereby affecting both local weather and global climate. At the same time, as suggested by the upper cycle, the climate change will affect the active layer and permafrost character. Summer warming, or winter warming with increased snow, will have different outcomes, though for large and long-term changes in climate, they will probably converge. The two cycles are shown linked through soil thermal conditions, but they are also linked through soil moisture. Both cycles have a direct impact on the hydrologic response of the landscape, including water storage for subsequent evaporation and runoff (Kane 1997). This scenario applies to upland ecosystems. Lowlands and wetlands may respond differently.

Table 5-1: Examples of how observed environmental changes may affect arctic ecosystems. Note that some changes can reverse direction depending on the local context.

CHANGING PHYSICAL ENVIRONMENT	**ECOSYSTEM IMPACTS**					
	Vegetation	**Wildlife**	**Biogeochemical Fluxes**	**Trace gas**	**Fire**	**Lakes and Streams**
Permafrost thaw	Slumping soils disrupt vegetation	Decrease in trafficability	Increased export of C, N, P and sediments	Increasing flux to atmosphere	Drainage promotes fire	Increased productivity/ sediment load
Soil moisture changes	Shifts in species distribution	Mixed response depending upon species	Increased export if runoff increases	CO_2 flux increases in drier soils, methane flux increases in wetter soils	Fire frequency and severity increases in drier soils	If runoff increases, productivity will increase
Summer temperature increase	Higher gross primary production and respiration	Increase in insects	Increased decomposition liberates nutrients	Decomposition leads to increases in fluxes	Fire frequency and severity increase	Lake trout and grayling growth decline
Snow cover decline	Shifts in vegetation stature and species	Less insulation for rodents. Predator species become more advantaged	Greater winter export	Fluxes may decrease if soils are colder due to lack of insulation	Increased fire	Less spring input of organic matter and nutrients lowers productivity
Winter temperature increase	Northward migration of species, increase in shrubs	Winter mortality decreases. Ice layers reduce fresh air to rodents	Decomposition rates increase during winter increasing soluble nutrients in spring	Fluxes increase	Longer fire season	Increases in baseflow throughout winter

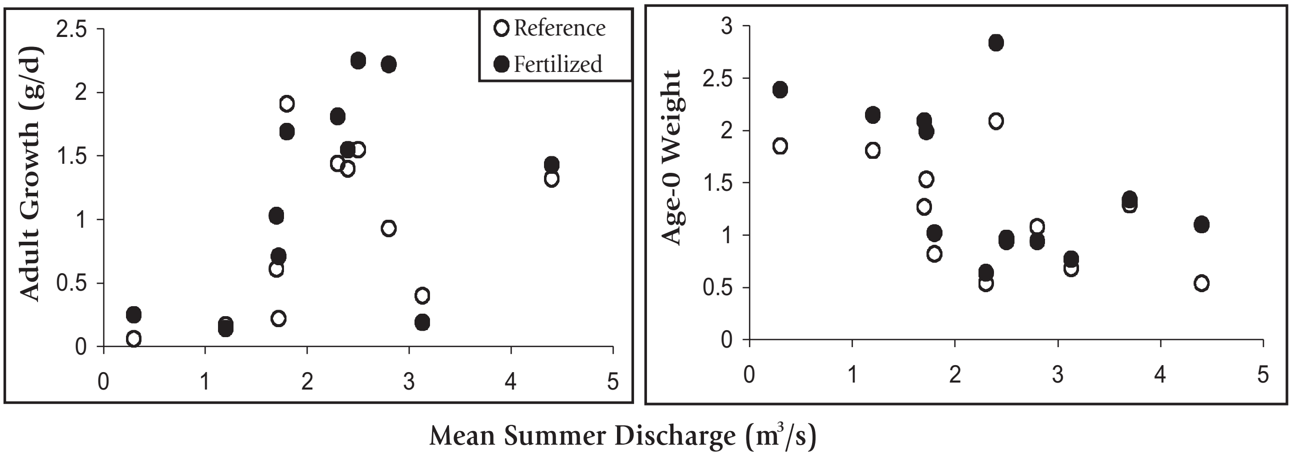


Figure 5-4. Discharge versus fish production in the Kuparuk River, Alaska. Instream biotic systems are linked closely to the behavior of river systems, with dependencies on both the physical (scouring, habitat) and chemical (oxygen status, primary production) setting. These dependencies on biotic systems are translated into dependencies on human society, both industrial and indigenous. Above is a plot of the average arctic grayling adult growth and young-of-the-year weight at 40-d versus mean discharge in the reference and fertilized reaches of the Kuparuk River, 1986, 1988–1998 (adult growth was not available for 1993). The impact of hydrological processes on biological processes is evident (Linda Deegan, Arctic LTER database).

nutrient flows and hence phytoplankton production on which marine food webs—and northern Atlantic commercial fisheries—depend (Gudmundsson 1998, Astthorsson and Gislason 1995, 1998, Hamilton and Allanson 2001). Marine mammals have a close dependence on sea ice for mobility and access to food sources.

Arctic Water Cycle Change and Humans

Environmental change across the Arctic influences human societies. Table 5-2 shows some of these "points of contact" between humans and the linked hydrological system. Industrial enterprises such as energy development, transportation, or commercial fisheries, and more traditional livelihoods and communities of the Arctic's indigenous peoples, are intimately connected to elements of the arctic hydrologic cycle. Changes to precipitation quantity and timing, fog, snow, river and sea ice, sea level, temperature, ocean circulation, and contaminants have, and will continue to affect individual livelihoods, the viability of settlements, and national economic prosperity for many who live in the Arctic. Precipitation changes associated with climate warming, such as that which killed thousands of reindeer on Svalbard (Aanes et al. 2000), point to the vulnerability of human-managed arctic ecosystems. Changes in permafrost could affect thousands of structures built on frozen ground—including houses, hospitals, pipelines, and community water systems—well into the future as the thermal and structural stability of soils continues to degrade (Figures 5-5, 5-6, 5-7). While the true impact of each of these changes requires an understanding of the complex interactions between physical, biological, and human systems, current studies are mostly limited to educated guesswork. Because arctic physical processes are tightly coupled to global processes, shifts in arctic water cycles could also have consequences for people far outside the Arctic. As an example, freshwater from the Arctic basin is important to global ocean circulation, including the North Atlantic Current that moderates the climate of northern Europe and perhaps aridity in central North America.

Table 5-2: Points of contact, and areas of needed research, where changing physical environment parameters are likely to affect human activities in the Arctic.

CHANGING PHYSICAL ENVIRONMENT	HUMAN DIMENSION IMPACTS				
	Infrastructure	**Transportation**	**Other Economic Activities**	**Subsistence, Traditional Activities**	**Health**
Permafrost	Buildings, water & power systems	Roads, runways	Pipelines	Overland travel, subsistence resources	Water supplies, waste disposal
Precipitation, runoff	Riverbank erosion, flooding, water supplies	Roads, navigable waters	Mining & industrial wastes	Overland travel, subsistence resources	Water-borne illness
Storms, fog	Coastal wave erosion	Sea, air	Fire prevention	Subsistence hunting & fishing	Accidents
Snow cover	Snow removal	Winter travel avalanches	Water supply	Overland travel, subsistence resources	Water supply
River & sea ice	Coastal/riverside erosion	Shipping routes & season	Hydropower	Subsistence hunting, travel	Accidents
Summer temperature	Foundation instability	Permafrost and ice-road degradation	Tourism	Changes in species and migration routes	Insects, vector-borne illness
Sea level	Coastal flooding, erosion	Shipping facilities	Village relocation	Coastal cemeteries or artifacts	Freshwater salinization
Ocean circulation	Harbor siting	Shipping	Commercial fisheries	Subsistence hunting & fishing	Contaminant transport
Contaminants	Water supply/ treatment	Spill prevention remediation	Commercial fisheries	Subsistence hunting & fishing	Human exposure

Land-Atmosphere-Ocean Feedbacks

Atmospheric circulation patterns change seasonally and have complex interactions with ocean circulation, sea ice, and land-surface energy and water fluxes. Among these interactions, the link between the atmosphere and snow cover extent is relatively well established. Snow cover influences the surface energy budget in winter by insulating the surface and in spring by recharging rivers. Clark et al. (1999; citing also Thompson and Wallace 1998) found that the Arctic Oscillation (AO) correlates with Eurasian surface air temperatures. Temperatures in turn affect snow cover. The observed recent decrease in Northern Hemisphere spring/summer snow cover (Groisman et al. 1994) thus likely reflects large-scale atmospheric events. Box 5-2 outlines some of the evidence linking northern hemisphere snow cover to atmospheric dynamics.

In chapter 4, we reviewed evidence for decadal-scale variability in Arctic Ocean ice. Recent data show significant losses of sea ice, especially in coastal and marginal seas. Several geophysical phenomena, including ventilation of the Arctic Ocean, deep-water formation, oceanic albedo, roughness, and evaporation, are dramatically altered by the presence or absence of sea ice. Box 5-3 illustrates some of these linkages.

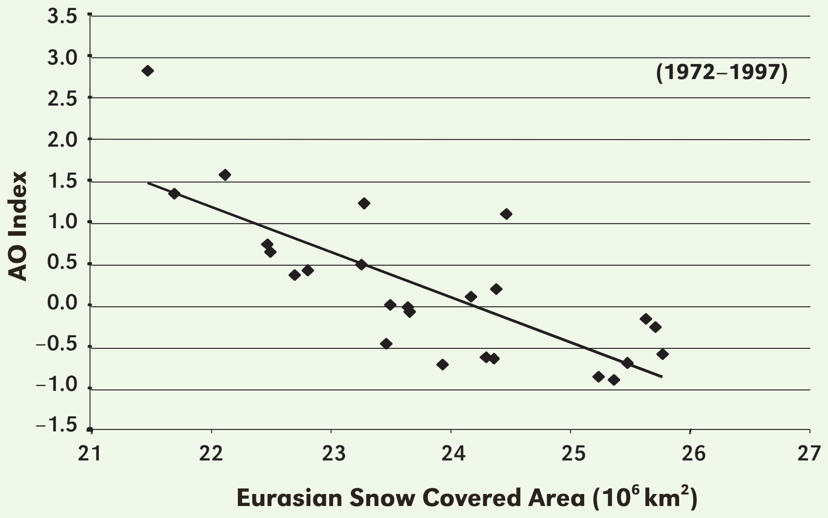
Figure 5-5. Structures can be dramatically affected if the underlying ice-rich permafrost thaws (photo by L. Hinzman).

Figure 5-6. The Trans-Alaska Pipeline is designed to keep permafrost frozen by the use of thermosiphons. Permafrost is warming in interior Alaska, where this picture was taken (photo by L. Hamilton).

Figure 5-7. Ice-rich permafrost thawing and surface and groundwater intensive flow created this thermokarst pit in a parking lot in Fairbanks, Alaska (photo by V. Romanovsky).

Arctic land-atmosphere-ocean feedbacks extend far beyond coastal seas and influence the Arctic Ocean as well as other oceans of the world. Recent analysis of periodic atmospheric phenomena such as the AO and NAO suggest interconnections among the major land, ocean, and atmospheric components of the larger arctic system (Hilmer and Jung 2000, Morison et al. 2000). Salinity anomalies originating with freshwater pulses from the Arctic have had oceanographic, climatic, and economic consequences around the northern Atlantic (Malmberg et al. 1999). Such observations give hints about how the system is woven together and its potential sensitivities to global change (Box 4-1).

Box 5-2. Large-Scale Circulation/ Snow Cover Linkages



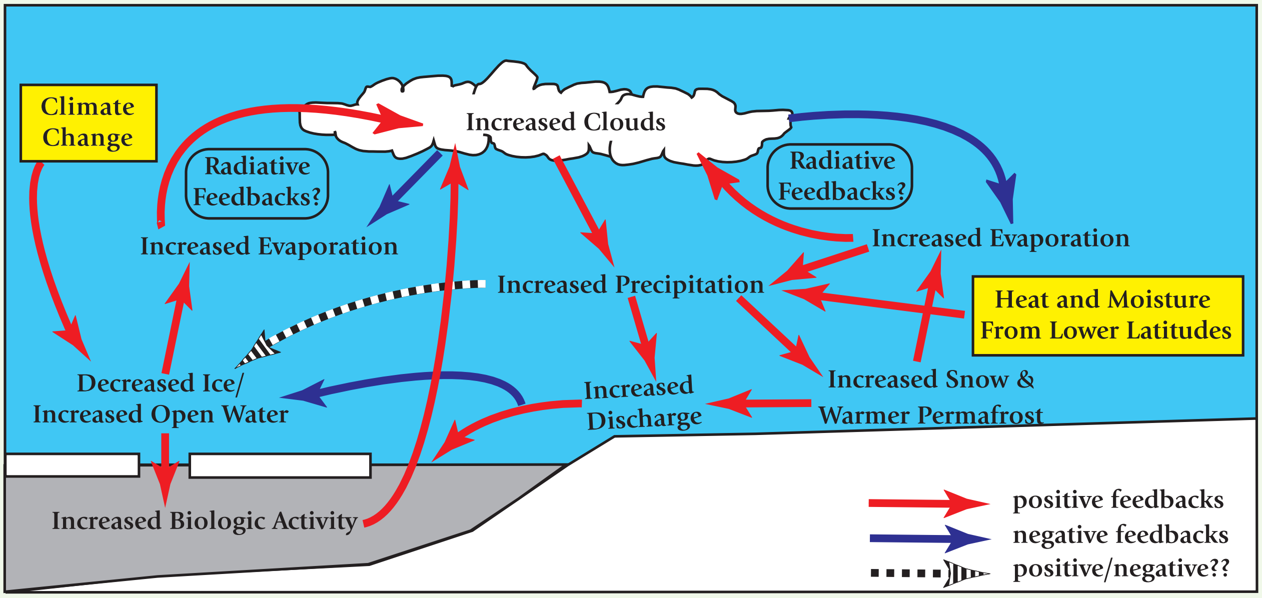
Interactions between the arctic land mass and overlying atmosphere have been found to have an important impact on the development and sustainability of snow cover and on arctic weather patterns. Several studies have shown how the atmosphere affects Eurasian snow cover (e.g., Clark et al. 1999). Other investigations have emphasized the atmospheric response to snow such as the relationship between anomalous Eurasian snow cover extent and the strength of the Asian monsoon (e.g., Douville and Royer 1996). Cohen and Entekhabi (1999) showed a statistically significant impact of autumn Eurasian snow cover patterns on the strength and spatial coverage of the Siberian high and how that can affect the position of the Icelandic low, resulting in shifts in the North Atlantic-Arctic atmospheric circulation. Large negative (positive) snow extent anomalies that exist in autumn can act as a heating (cooling) mechanism through albedo conditions and have an effect on the following wintertime atmospheric conditions (Watanabe and Nitta 1999). Figure is from Arsenault (2000).

Land-Atmosphere-Ocean-Human Feedbacks

The commercial fisheries of the North Atlantic, important economically to more than a dozen nations and as food sources to many more (Figure 5-8), are immediately "downstream" from the Arctic Ocean. Often, they have been directly affected by the arctic hydrologic cycle (see Box 5-4). It is possible to trace causal links from arctic winds and precipitation, to arctic and Atlantic oceanographic changes, to primary biological production and key fisheries resources. The health of these resources in turn affects the well-being of people, enterprises, communities, and even nations. The cold-ocean ecosystems of the northern Atlantic support some of the most fisheries-dependent societies on Earth. Marine resources are critical as well to many arctic and sub-arctic indigenous communities, for whom subsistence hunting and fishing provide cultural continuity and significant sources of food. Water fluxes also regulate the spread and bioaccumulation of contaminants, originating both from northern and more distant sources, in arctic wildlife (AMAP 1999). Such contaminants are understandably of great concern to arctic residents (Figure 5-8). Airborne transport of pollutants and deposition through precipitation constitute a major transboundary environmental issue (Figure 5-9).

Other important land–atmosphere–ocean–human connections linked through the water cycle affect arctic industrial activities and

Box 5-3. Feedbacks Among Sea Ice, Precipitation, River Runoff, and Coastal Oceans

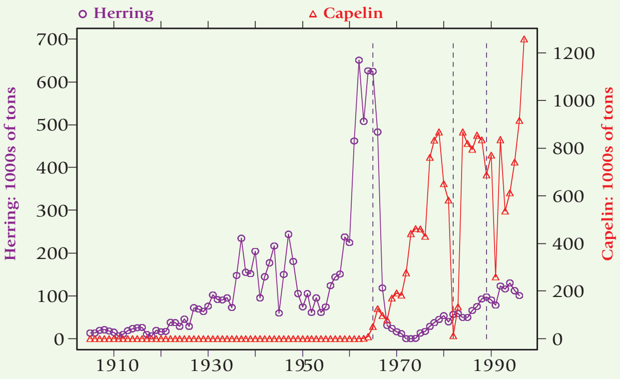


Recent studies indicate the presence of decadal-scale variability in the extent and thickness of arctic sea ice. Recent trends show decreasing sea ice, especially in coastal and marginal seas. The box diagram shows some potential land-ocean-ice-atmosphere feedbacks and interactions that might occur in such a changing environment.

We start with an assumption of decreasing sea ice cover near the coast in response to climate warming, which would encourage cloud formation and increased precipitation. More open water fosters a potential biotically mediated positive feedback on clouds through production of dimethyl sulfide (DMS) by marine phytoplankton. DMS then serves as a source of cloud condensation nuclei. We also note the potential for additional water vapor advected to the coastal region from the central Arctic Ocean and/or lower latitude areas. In summer, increased precipitation would create more runoff and thus more discharge of fresh waters to the coastal ocean. A potential negative feedback might then result, since all other effects being constant, freshwater tends to stratify the coastal ocean and encourage sea ice growth. (In fact, the annual volume of river discharge to the Arctic Ocean approximately equals the volume of sea ice exported southward through Fram Strait.) However, positive feedbacks could also occur as the stratified ocean warms (Macdonald 2000).

The above scenario assumes that the land surface is fixed. In reality, increased precipitation might encourage a warming of the land surface, for example, as the insulating effects of snow cover act to warm permafrost. This might lead to plant community changes, increased evaporation and thus more clouds, more precipitation, and so on. We also note the potential for radiative feedbacks in this scenario, yet predicting cloud properties and their specific response to perturbation will constitute a major challenge. An important caveat is the presence of lateral advection, which would certainly produce a three-dimensional structure that is not captured by this two-dimensional schematic. The unknowns and uncertainties are many, and the hydrological cycle figures prominently in each.

Box 5-4. Freshwater Fluxes, Ocean Salinity, and Fisheries



The graph above shows total catches in Icelandic waters of herring and capelin, 1905 to 1997. Dashed vertical lines show approximate arrivals of cold, low-salinity arctic water anomalies (GSA '70s and GSA '80s) off North Iceland. These anomalies have strong linkages to the water cycle and affect biological production of importance to humans.

The "Great Salinity Anomaly" (GSA '70s), a low-salinity surface water mass that circulated around the North Atlantic ca. 1968–82, is thought to have originated with a freshwater/sea ice pulse from the Arctic via Fram Strait. A second North Atlantic salinity anomaly (GSA '80s) that circulated ca. 1982–89 had different origins, forming in the Labrador Sea/Baffin Bay due to severe winters and possibly arctic freshwater outflow through the Canadian Archipelago (Belkin et al. 1998). Arctic hydrological factors, including precipitation and runoff in northern Canada, and the sea-ice extent in the western Arctic Ocean, are thus linked (Power and Mysak 1992, cited in Belkin et al. 1998) to a phenomenon that has been described as "one of the most persistent and extreme variations in global ocean climate yet observed in this century" (Dickson et al. 1988). As they moved for years through the North Atlantic, both GSAs had effects on marine life, commercial fisheries, and human societies.

The seas north of Iceland are characterized by relatively large variations in temperature and salinity in comparison with seas to the south. These variations affect phytoplankton production: a cold, fresh surface layer inhibits vertical mixing, reducing the nutrients available to maintain the spring phytoplankton blooms (Gudmundsson 1998). Phytoplankton production controls the biomass of zooplankton, which in turn provides food for larval cod, capelin, and herring (Astthorsson and Gislason 1995). The cold, relatively fresh water of GSA '70s was first observed northeast of Iceland in 1965–71, coinciding with the collapse of Iceland-waters herring catches seen in the graph above (Hamilton and Allanson 2001). Herring stocks never fully recovered from this collapse. In subsequent years another forage species, capelin, played a larger commercial role. GSA '80s circulated through North Icelandic waters in 1982, and again in 1989–90. Both these events were followed by steep falls in capelin catches.

Onshore in Iceland, fluctuating fisheries catches translated into economic hardship for individuals and businesses who count heavily on these resources. Some employers were forced to shut down and some communities lost inhabitants as well as jobs.

A capelin catch in southeast Iceland (photo by Larry Hamilton).

settlements. Development and maintenance of infrastructure in arctic regions is thoroughly intertwined with permafrost-dominated hydrological processes. Facilities built over permafrost remain stable only so long as the permafrost remains frozen. A weak understanding of hydrologic science and a warming climate combine to make construction and maintenance of infrastructure tenuous.

Construction of roads or bridges requires knowledge of the biogeophysical characteristics of the drainages that must be traversed. These include the frequency of floods, average high and low flows, potential for icing, rainfall distributions, snow loads and dominant drift directions, soil properties, and vegetation. For most regions of the Arctic, such information is essentially nonexistent. This often leads to costly mistakes and extensive re-engineering. Construction or removal of roadways also threatens to damage fragile ecosystems that will require decades or centuries to recover. Roads create impoundments of water, which if not properly drained can result in extensive thermokarsting (Figure 5-7). All of these issues become especially problematical under rapid environmental change and highlight the role of humans in the interacting arctic biogeophysical system.

Central Questions: What are the impacts of arctic hydrological changes on ecosystems and humans? How does the hydrologic cycle feed back to the oceans and atmosphere?

Key Gaps in Current Understanding and Needed Studies:

- Synthesis studies coupling atmosphere-land-ocean dynamics
- Permafrost impacts on vegetation, biogeochemistry, and trace gas exchanges
- Documentation of changes in the distribution and dynamics of arctic vegetation
- Documentation of changes to arctic animal populations, many of importance to humans
- Altered weather and human response
- Sensitivity of human infrastructure to permafrost warming and associated hydrological change
- Synthesis studies embedding human dimension issues into coupled atmosphere-land-ocean system studies

Figure 5-8. Fish are an important part of the subsistence diet and the commercial economy for many arctic people. This Native family is harvesting salmon on the Arctic Red River in the Northwest Territories, Canada (photo by L. Hinzman).

Figure 5-9. Sulfur dioxide and other pollutants from this smelter in the Murmansk region of Russia have killed forests in an area more than 40 kilometers across and caused measurable damage well into Norway and Finland (photo by L. Hamilton).

6

Implementation of Arctic-CHAMP

Arctic-CHAMP must be inclusive and structured to enlist a continuing input of new ideas from the scientific community at large. The initiative also requires a "corporate identity" through which scientists can propose and participate in the monitoring, modeling, and process study components of the initiative. The committee envisions this identity-building to be aided by an Arctic-CHAMP steering committee, an institutional home for the program, research plans, and a workshop series. A successful Arctic-CHAMP should complement, contribute to, and draw from other important NSF, federal agency, and international arctic initiatives. These issues are articulated as a set of specific recommendations to NSF, mapped to the scientific and technical requirements of Arctic-CHAMP identified throughout earlier portions of this report (Box 6-1).

- **This committee recommends that an Arctic-CHAMP Scientific Steering Committee (AC-SSC) be formed to catalyze conceptual development of Arctic-CHAMP and to provide ongoing supervision of its execution.**

The AC-SSC should constitute an interdisciplinary advisory board, with representatives from the fields of land surface hydrology, atmospheric dynamics, sea ice and ocean studies, terrestrial and aquatic ecology, and socioeconomics. In addition, membership should include scientists active in executing large-scale synthesis studies, specifically, those developing earth and arctic systems models. A balance between process-level field researchers, operational monitoring agency representatives, and simulation modelers should be sought. The charge of AC-SSC will be to set the science agenda of the overall initiative, to coordinate its research activities, and to ensure that results are disseminated to a broad user community. The AC-SSC should critically assess the initiative's progress and scientific relevancy, as well as provide guidance to NSF-ARCSS on future funding requirements. To ensure continuity across NSF arctic research programs, the AC-SSC should be represented on the ARCSS Committee.

- **The committee recommends that an Arctic-CHAMP science agenda should be more fully developed through an interdisciplinary implementation plan.**

A detailed science plan should go beyond this current document, presenting guidance on the institutional structure for Arctic-CHAMP, its governance, a set of specific scientific investigations and observational campaigns, and coordination with other NSF, national, and international agency efforts. The implementation plan would be augmented through annual reports summarizing progress on Arctic-CHAMP and providing revised plans for future work. Additional documentation of progress would be provided through, first and foremost, peer-reviewed publications by participating researchers. A newsletter, workshop reports, and a frequently updated web page would also help to promote a broad following.

- **The committee strongly recommends that NSF support a set of multidisciplinary, process-based catchment studies.**

Through the normal peer review process, NSF should identify and fund experiments at a core group of field sites aimed at developing a mechanistic view of the hydrology of the Arctic. Integration of hydrology, land-atmosphere interaction, biology, and biogeochemical processes should be a fundamental feature of this research. An emphasis on up-scaling to ensure the relevancy of these studies to the full pan-arctic domain is encouraged.

- **The committee recommends an immediate and major effort to improve our current monitoring of water cycle variables across the pan-Arctic.**

Detecting and interpreting progressive changes to the arctic hydrologic cycle will be impossible without a coherent observational strategy. This requires immediate attention as well as long-term vigilance. NSF should invest in an expanded, hydrologically oriented monitoring program across the pan-Arctic, coordinating, as required, with U.S. and international agency partners. Enhancing our current capacity will involve data rescue, expansion of current observational networks, and development of new technologies for harsh weather instrumentation. It should also foster development of new interpolation and remote sensing techniques to achieve pan-arctic coverage at high spatial and temporal resolutions.

- **This committee recommends creation of an Arctic-CHAMP Synthesis and Education Center (CSEC) to serve as the institutional focal point for the initiative, open to the entire community of arctic researchers.**

We recommend NSF create a central facility to catalyze ongoing synthesis studies of pan-arctic hydrology. Arctic-CHAMP synthesis models would be developed at CSEC. The center should lead the coordination of modeling, field research, and monitoring efforts within Arctic-CHAMP. Each developmental version of the Arctic-CHAMP models would reside at CSEC, but when sufficiently mature, distributed to the broader research community. In coordination with the National Snow and Ice Data Center (Boulder, Colorado), CSEC would produce a continually evolving Arctic-CHAMP Hydrometeorological Data Archive (HDA) for station-based monitoring data and value-added project outputs emerging from the synthesis work. Arctic-CHAMP science

Box 6-1. Arctic-CHAMP Scientific and Technical Needs

Several specific research needs aimed at improving our current understanding of the arctic water cycle and its sensitivity to change were identified throughout the text, setting the scientific stage for Arctic-CHAMP. In response to the integrative nature of the arctic water cycle, these issues will need to be addressed in a systematic and comprehensive fashion. A synthetic view of the entire pan-arctic hydrologic system, based on focused process, feedback, and sensitivity studies, will be critical to ensure the necessary transfer of knowledge between fine and large scale studies and between campaigns dedicated to observation and process understanding. Specific activities that are required to develop such an integrated view of the entire pan-arctic system include:

- **maintenance of existing and establishment of new, long-term, and coherent monitoring programs for key hydrological and biogeochemical variables, including both water itself and the constituents it supports;**
- **enhancement of the current generation of field programs to support process-based understanding of arctic hydrology;**
- **development of methods to bridge the gap between process-level studies, point-scale monitoring, and the hydrodynamics of the pan-Arctic through combined field-based measurements, remote sensing, and modeling;**
- **design of a strategy to achieve synthesis and water budget closure over the full water cycle, encompassing interactions across atmospheric, land surface, and oceanic components with links to the larger earth system;**
- **determination of the links between water-related changes, ecosystem dynamics, biogeochemical cycling, and trace gas emission which feed back to the hydrologic cycle and climate system;**
- **assessment of the vulnerability of humans to arctic water cycle changes;**
- **full-system feedback and sensitivity studies, including human systems, in response to global change; and**
- **implementation of a viable administrative structure and mechanism to promote full pan-arctic system integration.**

A more exhaustive listing of recommended actions representing the views of a broad cross-section of the arctic science community is presented in a collection of position papers (Hinzman and Vörösmarty 2001). Appendix 2 offers a summary listing of these issues.

activities will serve as an important application of state-of-the-art technologies and should be coordinated with relevant activities of the NSF Information Technology Research Program.

Researchers and their students and post-docs would be chosen through a competitive fellowship program attracting the most highly qualified applicants. CSEC would bring together observationalists, process-level scientists, and modelers in a collaborative physical setting to share insight and to cross-fertilize ideas. Research would be performed by graduate students and post-doctoral fellows on site, but supervised by contributing researchers from several parent institutions. A useful model for CSEC is that of the NCEAS (National Center for Ecological Analysis and Synthesis in Santa Barbara, California). To inform the public of the need to study the otherwise distant Arctic and its role in environmental change, direct links to the NSF Interagency Education Research Initiative are advised. A vigorous K-12 effort could be mounted through the CSEC.

- **This committee recommends that funding be committed to an Arctic-CHAMP Workshop Series and Open Science Meetings to provide ongoing intellectual support for the overall initiative.**

Arctic-CHAMP would serve as an excellent focal point for working groups seeking to execute field programs, create and implement community-based models, and interpret specific observational data sets. A major initial effort should be directed toward understanding the changing contemporary condition of the pan-arctic water cycle. Other workshops in the series could focus on historical/paleo and future settings. Biogeophysical and human dimension issues should be jointly addressed. Periodic Open Science Meetings should also be convened to solicit input from the broader research community.

- **The success of Arctic-CHAMP will depend on a purposeful integration across other programmatic elements of the National Science Foundation and allied federal agencies, and the committee strongly advises that steps be implemented to foster this collaboration.**

A primary goal of the current NSF-ARCSS Program (Box 6-2) is to promote an understanding of the impacts of global change on the physical, biological, and human resources of the Arctic (ARCUS 1998). The issue of feedbacks across the pan-Arctic is an important emphasis of the future ARCSS Program and thus integrates well with the concept of an Arctic-CHAMP. This interdisciplinary perspective is driven not only by scientific curiosity but as well by the needs of the policy community, which seeks response strategies to impending climate change that transcend the domains of traditional disciplines (e.g., U.S. National Assessment 2000).

By their very nature, multiagency efforts such as the U.S. National Assessment and SEARCH would serve as important sources of information and would be served, in turn, by the unique set of hydrologically oriented results emerging from Arctic-CHAMP. As a good example, remote sensing for freeze-thaw dynamics, envisioned as a NASA post-2002 mission (Cline et al. 1999), would provide an enormously important data set for hydrological studies across the entire pan-Arctic. Coordination with Arctic-CHAMP field studies could provide critical ground-truth, while Arctic-CHAMP simulation studies would constitute an immediate hydrological application for this satellite system. Arctic-CHAMP studies on biological and biogeochemical feedbacks in response to global change would directly support the central scientific concerns of the NSF Biocomplexity Program. A coordination is clearly needed to avoid duplication of effort and to optimize the use of federal research dollars. Appendix 3 lists several specific opportunities for collaboration within the U.S. Arctic research community.

- **There are several ideal opportunities for international collaboration in arctic hydrological research. The committee urges an active linkage of these ongoing programs with Arctic-CHAMP.**

Arctic-CHAMP's treatment of coupled water dynamics across the entire pan-Arctic will enlist the interest and involvement of the international research community. There are several well-established experimental, monitoring, and analysis programs in place to which Arctic-CHAMP should be linked, with the aim of providing synergistic benefits not otherwise achievable through each individual effort. These involve significant ongoing as well as new initiatives organized around scientific and monitoring activities. Box 6-3 summarizes several noteworthy efforts. Among these are major arctic field campaigns over a variety of spatial scales, routine environmental monitoring, intercomparison modeling studies, remote sensing, numerical weather prediction and reanalysis, data archiving activities, and policy-relevant assessments. Bilateral agreements involving the U.S. and other arctic scientific partners should be fostered, in particular with Russia to help sustain its scientific infrastructure and human resources.

- **The Arctic, as a harbinger of global climate change, will continue to be an important focal point for ongoing research and international policy formulation. It is recommended that a policy arm of Arctic-CHAMP be established to disseminate scientific findings to the environmental management community.**

Box 6-2. NSF ARCSS Program Elements

As a consequence of its ambitious mandate, ARCSS has been organized into a series of more manageable programmatic components:

- **Land-Atmosphere-Ice Interactions (LAII);**
- **Ocean-Atmosphere-Ice Interactions (OAII);**
- **Paleoenvironmental Studies (Greenland Ice Sheet Project Two [GISP2], Paleoclimates from Arctic Lakes and Estuaries [PALE]), both part of Paleoenvironmental Arctic Sciences (PARCS);**
- **Human Dimensions of the Arctic System (HARC); and**
- **Russian-American Initiative on Shelf-Land Environments (RAISE).**

The LAII Flux Study in Alaska, North American Tundra Experiment (NATEX), Arctic Transitions in the Land-Atmosphere System (ATLAS) program, and U.S. contributions to the International Tundra Experiment (ITEX) provide important observational components to the overall ARCSS effort. These studies have supported a broad array of observational programs, process-based studies, modeling efforts, and environmental assessments. Several have been high profile and highly successful (e.g., Greenland Ice Sheet Project, SHEBA), both scientifically and in raising public awareness of the importance of the Arctic in global change. While these programs provide important new science, synthesis across these efforts has yet to be achieved. Integration and synthesis is emphasized as part of the new ARCSS research agenda.

It is noteworthy that ongoing IPCC assessments include a polar regional analysis, due to the many years of research indicating a high sensitivity of the Arctic to greenhouse warming. Integrative, pan-arctic understanding of hydrologic interactions and feedbacks in response to global change—of the type envisioned for Arctic-CHAMP—provides critical scientific support to U.N. Framework Convention activities. The international diplomacy issues associated with arctic system change are enormous. The contributions of Arctic-CHAMP toward articulating the diverse physical, biological, and human vulnerabilities to this change provide an important impetus for international cooperation in wisely managing this critical part of the arctic and earth systems.

Box 6-3. International Programs Sharing the Scientific, Observational, and Policy-Oriented Objectives of Arctic-CHAMP

Several opportunities are apparent for mutually beneficial collaboration, taking advantage of existing infrastructure and ongoing investment in these programs. The listing below shows some major representative programs and is not meant to be exhaustive.

INTERNATIONAL PROGRAM	PRIMARY GOALS/ACTIVITIES
Major International Science Initiatives	
1. World Meteorological Organization's World Climate Research Program (WMO/WCRP)	
(a) Global Water and Energy Experiment (GEWEX)	Coupling studies of land-atmosphere for regional and global modeling; Continental-Scale Experiments (CSE's) include Baltic Sea (BALTEX), Mackenzie GEWEX Study (MAGS), GEWEX Asian Monsoon Experiment (GAME) for Lena River; organizing major Coordinated Enhanced Observation Period (CEOP) for 2001–02.
(b) Climate Variability and Predictability Study (CLIVAR)	Understanding climate variability on a months-to-decades time frame.
(c) Climate and Cryosphere (CliC)	Broad set of cryosphere/atmosphere interactions (snow, ice, land, sea ice, oceans); Arctic as harbinger of global change; strong monitoring component including WMO meteorology and hydrology networks; follow-on to existing Arctic Climate System Study (ACSYS).
2. International Geosphere-Biosphere Program and Subsidiary Program (IGBP) Elements	
(a) Past Global Changes (PAGES)	Response of earth system to change over numerous time domains including rapid climatic shifts; analysis of sea ice, salinity, thermohaline circulation under current versus glacial maximum conditions, paleoclimatic reconstructions along Pole-Equator-Pole (PEP) transects; paleoclimate modeling including dynamic vegetation; human dimension issues during the Holocene.
(b) Task Force of Global Analysis, Interpretation, and Modeling (GAIM)	Development of linked models of the complete earth system, integrating dynamic atmosphere, ocean, biosphere, and biogeochemical models; feedback studies and system sensitivity to global change.
(c) Biospheric Aspects of the Hydrological Cycle (BAHC)	Enhancements of land surface-atmosphere transfer schemes; design and execution of large-scale field experiments; monitoring of carbon, water and energy fluxes at instrumented sites; constituent transport across drainage basins; dynamic vegetation and its role in regulating climate.
(d) International Global Atmospheric Chemistry (IGAC)	Biosphere-atmosphere exchanges of trace gases, including arctic wetlands; development of new gas emission instrumentation.

INTERNATIONAL PROGRAM	PRIMARY GOALS/ACTIVITIES
Intercomparison Studies	
(a) GEWEX/ACSYS Project for Intercomparison of Land Surface Parameterization Schemes (PILPS-2e)	Improve arctic land surface transfer schemes through multiyear, spatial comparisons of participating model results; explore alternative treatments of snowpack, soil, permafrost, frozen lake, wetland dynamics.
(b) International Association of Hydrological Sciences Snow Model Intercomparison Project (SNOWMIP)	Improve understanding of snow/hydrology process-level linkages.
(c) WMO Commission for Instruments and Methods of Observation: Solid Precipitation Measurement Intercomparison	Correction of well-known biases in precipitation measurements.
(d) IGBP Paleo-Model Intercomparison Project (PMIP)	Assess relative performance of models contrasting glacial maximum (20K years before present) to Holocene altithermal (6K bp).
(e) European Ice Sheet Modeling Initiative (EISMINT)	Test, compare, improve upon numerical ice-sheet, ice-shelf, and glacier models.
(f) ACSYS Sea Ice Model Intercomparison Project (SIMIP)	Improve understanding of freshwater dynamics associated with growth, transport, and decay of Arctic Ocean sea ice.
(g) Arctic Ocean Model Intercomparison Project (AOMIP) of ACSYS-CliC	Understand processes influencing Arctic Ocean climate and how to best represent and forecast these in numerical models.
Existing Field/Process Study Sites	
(a) U.S. and International Long-Term Ecological Research Network (LTER/ILTER)	Two LTER sites with integrated research, intensive monitoring, and experimentation. Two other sites beginning to develop long-term and integrated research.
(b) International Tundra Experiment (ITEX)	MAB-NSN initiative (Man-And-the-Biosphere, Northern Sciences Network); provides systematic meteorological station data, monitoring of permafrost in collaboration with IPA, snow cover and lake ice data, and analysis of permanent plot studies.
(c) Northern Hemisphere Climate-Processes Land-Surface Experiment (NOPEX)	Long-term catchment studies, soil-plant-atmosphere monitoring, regional climate surveys, use of remote sensing for data inputs to models, development of cold-weather measurement techniques.
(d) BOREAS	Major U.S.-Canadian initiative to develop improvements in understanding of land surface-atmosphere exchanges of energy, water, carbon, and other biogeochemical fluxes, including trace gases; bulk of field effort ended in mid-1990s, analysis continues.
Remote Sensing	
(a) Glacier Inventory of the Commission on Glaciation, International Union for Quaternary Research (INQUA)	Based on Landsat-7 data, provides benchmarks for future change in freshwater stocks trapped on land as “permanent” ice.

INTERNATIONAL PROGRAM	PRIMARY GOALS/ACTIVITIES
(b) Cryosphere System Program (CRYSYS) (Canadian contribution to NASA Earth Observing System)	Develop methods to extract and use cryospheric information from satellite and more conventional data sources.
(c) European Space Agency (ESA) Synthetic Aperature Radars on ERS-1 and ERS-2	Provide altimetry for monitoring changes in glacial ice mass.
(d) ESA's CryoSat	Set for launch in 2003, will fly a radar altimeter to monitor ice sheets and marine ice.
(e) Canada's RADARSAT	Provide synthetic aperature radar (SAR) imagery with high resolutions, from 8 to 100 m; backscattering holds potential for mapping freeze-thaw of surface active layer.
Monitoring and Analysis Programs	
(a) Global Climate Observing System (GCOS)/ Global Terrestrial Observing System (GTOS)	Multiorganizational (WMO/UNESCO/UNEP/ICSU) operational framework for systematic change detection; GCOS Surface Network (GSN) would serve as a global reference network of land surface observational weather/ climate stations; Global Terrestrial Networks (GTN) would include measurements of high relevance to northern polar region including glacier inventories (GTNet-G), hyrology (GTN-H), permafrost (GTNet-P).
(b) World Glacier Monitoring Service	Glacier monitoring providing inventories of glacier numbers, areal extent and in some cases glacier mass balance.
(c) International Permafrost Association (IPA)	Site-specific time series and pan-arctic mapping of permafrost; two international programs constitute IPA observational activities: the Circumpolar Active-Layer Monitoring (CALM) and Permafrost and Climate in Europe (PACE); NSIDC holds the IPA Circumpolar Active-Layer Permafrost System (CAPS) CD-ROM.
(d) Arctic Paleo-River Discharge (APARD)	Multi-disciplinary analysis of modern and ancient circumarctic river discharge, initiated by the Arctic Ocean Sciences Board (AOSB).
Numerical Weather Prediction and Reanalysis	
(a) European Center for Medium-range Weather Forecasting (ECMWF) and National Center for Environmental Prediction (NCEP)	Forthcoming ECMWF ERA-40 global reanalysis will provide long time series (1957–present) of atmospheric variables at 60-km resolution and six-hourly time steps; precipitation, evaporation, net vapor convergence, winds, radiation fluxes, and clouds will be routinely computed; U.S. reanalysis efforts (1948–present) established under NCEP.
(b) ACSYS Panel on Polar Products from Reanalysis Working Group on Coupled Models Numerical Experimentation Group (ACSYS NEG)	Activities to support use of weather prediction and atmospheric reanalysis models with arctic focus; under WCRP auspices.
Data Archives	
(a) National Snow and Ice Data Center (NSIDC)	Clearinghouse for a broad array of data sets supporting polar and high-latitude studies, including historical station time series and remote sensing data sets, several

INTERNATIONAL PROGRAM	PRIMARY GOALS/ACTIVITIES
	directly linked to the arctic hydrologic cycle (e.g., precipitation, snow cover, sea ice extent); serves as NSF-ARCSS, NASA, and ISCU data center for arctic geophysical data products.
(b) Arctic Precipitation Data Archive (APDA)	ACSYS product from WMO Global Precipitation Climatology Center (GPCC).
(c) ACSYS Data and Information Service (ADIS)	Metadata directory of historical or newly available arctic data sets.
(e) Global Observing Systems Information Center (GOSIC)	Data clearinghouse for GCOS/GTOS/GOOS databases.
(f) Arctic Environmental Data Directory (AEDD)	Metadata system; archive nodes at USGS offices in Anchorage, UNEP GRID (Arendal, Norway), Russian Ministry of Environment Protection and Natural Resources (Moscow).
(g) Global Runoff Data Center (GRDC)	Archive of Arctic River Database (ARDB) housed in WMO-GRDC, Federal Institute of Hydrology, Koblenz, Germany.
(h) Pan-Arctic Hydrographic Data Base (R-ArcticNET)	Compendium of time series of runoff and discharge data across pan-arctic domain, conjoining USGS, Russian State Hydrological Institute (SHI), Environment Canada data; a collaboration of the University of New Hampshire and SHI; distributed by NSIDC.
Framework Convention on Climate Change	
(a) Working Group 1 (Science of Climate Change)	Quantitative documentation of progressive environmental changes due to greenhouse warming; Arctic recognized as highly sensitive to global climate change; observational support from GCOS/GTOS.
(b) Working Group 2 (Impacts, Adaptations, Mitigation)	Studies of biogeophysical changes and policy-relevant human dimensions issues.
Other Arctic Assessment Programs	
(a) Arctic Monitoring and Assessment Program (AMAP)	International program case as broad assessment of contaminant pollution across the pan-arctic, with consideration of associated impacts.
(b) Arctic Climate and Impact Assessment (ACIA)	Evaluation and synthesis of climate variability, change, and UV radiation increases; contributes an arctic perspective to IPCC, established under the Arctic Council.
(c) Northern Research Basins (NRB)	Symposium convened every two years to share research results from studies in watersheds dominated by snow, ice, and permafrost.

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Appendix 1
NSF-ARCSS Arctic Hydrology Workshop Participants

National Center for Ecological Analysis and Synthesis, Santa Barbara, California, 18–20 September 2000

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Appendix 2
Current Gaps in Understanding the Pan-Arctic Hydrological Cycle

The listing below was drawn from the set of key, unresolved scientific and technical issues that were solicited from participants of the NSF-ARCSS Arctic Hydrology Workshop, held at the National Center for Ecological Analysis and Synthesis, Santa Barbara, California, in September 2000. This listing is organized by the major domains over which the water cycle plays an integrative role: land, oceans, atmosphere, society (see Figures 1-1, 1-3, 2-1, 2-2). A subset of these issues has been identified and further articulated in the main body of this report.

Land Systems

Scientific Questions

- What would be the river response to extreme Holocene climatic events?
- How is spring meltwater partitioned into infiltration and runoff?
- What is the relative role of soil moisture dynamics in relation to other hydrological processes?
- What is the role of wind-pumping convection in arctic depth hoar and what is the importance of hard slab and snow dune formation processes?
- What determines the regional and temporal distribution of snow trends? Is it tied to the AO?
- How important is lateral transfer of heat during snowmelt?
- What are the mechanisms of vegetation-snow feedback?
- What is the role of vegetation in water budgets and how does it vary in space and time?
- What is the affect of boreal forests on pan-arctic hydrologic processes?
- Is there widespread drying of soil and ponds across the pan-Arctic in response to regional warming trends, and if so what is its impact on resident ecosystems?
- What is the distribution and importance of rock glaciers and rock fields as a source of late summer arctic discharge?
- What controls basin morphology in watersheds underlain by permafrost and how will it change with a warming climate?
- How does the fact that sediment is immobile (frozen) at the time of maximum stream power affect the sediment load in arctic rivers?
- What are the pathways of sediment discharged into the continental shelves by the arctic rivers and is the variability of this sediment delivery large enough to be represented in paleorecords?
- What is the timing and magnitude of sediment, carbon, and nutrient loads from hillslopes to large rivers and what is the effective constituent discharge of ice-affected rivers?
- How will sediment and other constituent discharges change as permafrost distribution responds to climate warming?
- What are the controls on the transfer of nutrients and organic matter from soils to streams across the pan-Arctic?

Technical Needs and Uncertainties

- Study energy, water, and carbon cycles as a linked system.
- Develop methods to quantify historic levels of soil moisture.
- Quantify the cumulative impacts of industrial and civil development on hydrologic systems.
- Improve understanding of water storage and subsurface flow processes in discontinuous permafrost and mountainous regions.
- Improve understanding of the surface heat and mass transfer processes in mountain regions.
- Better define the role of geometric patterns of permafrost degradation and its ecological and hydrological consequences.
- Develop better understanding of hydraulic routing through

glaciers; models of glacier runoff need better depiction of water dynamics at the base of the glaciers.

- Improve understanding of groundwater fluxes, including dynamics during winter.
- Sublimation needs better quantification.
- Methods need to be developed for improved mid-winter discharge measurements in high-latitude rivers.
- Wind-blown flux of snow and its redistribution is a critical unknown.
- Winter wind speed and direction often unreliable due to riming/icing of sensors; improved technology is required.
- Reliable methods to provide electrical power to remote weather stations need to be developed.
- Stratigraphy is hard to measure widely but determines critical bulk thermal and physical properties of arctic soils.
- Accurate and widespread measurement of winter precipitation not yet achieved.
- Improve upon the quality and documentation of observing techniques for making precipitation measurements.
- Link NSF arctic hydrological initiatives more closely to GEWEX/Mags, Crysys/ACSYS/CLiC.

Data Needs

- Quantify paleoclimatic forcing fields.
- Requirement for long-term observations of soil moisture at stations with climate data.
- Need for time series of discharge along the Arctic Coast that is ocean model-ready (including gauged and ungauged, chemistry, pollutants, sediments and heat).
- Accurate digital elevation models and vegetation maps necessary for hydrological studies.
- Thermal and hydraulic properties of frozen soils need to be sampled more systematically.
- Critical need for permafrost temperatures and distribution, including active zone dynamics.
- Measure the spatial and temporal variation of P-E around the Arctic.
- Develop and apply standard methods of precipitation measurement and correction.
- Fully quantify and map current glacier-covered areas to provide baseline for change.
- Need more arctic glacier mass balance measurements.
- Data rescue of hydrology observations from former USSR.
- Assessment of hydrometeorological data across national and other administrative borders is necessary due to wide array of sampling equipment.
- Need streamflow from a wide range of watershed scales.
- Snow cover depth maps derived from remote sensing or meteorological inputs need to be harmonized and cross-validated.
- Conventional networks are under severe cost pressures and automation leads to loss of key data and data degradation.
- Develop baseline data set of chemical (nutrient, sediment, contaminant, tracer) flux from all rivers in the Arctic Basin.

Scaling-Related Issues

- Do processes in the headwater basins really matter when modeling large basins and regions?
- New methods are necessary to scale hydrologic fluxes across basin sizes, from smallest headwaters to scale of the pan-Arctic.
- Improved techniques are needed to rescale hydrologic processes from points to GCM domains.
- Creation of gridded data sets by interpolation of sparse data across space and time requires additional attention.

Modeling and Related Analysis

- Need extensive soil moisture modeling over cold regions.
- Need improved methods for remotely sensing soil moisture over large areas.
- Snow sub-grid distribution variations by modeling or remote sensing remains a need.
- Spatial variation of snow cover insulation and density (snow water equivalent) is currently poorly articulated.
- Validation of model outputs of snow cover, snow water equivalent, snow depth, and precipitation is required.
- Develop and verify models of mass transport from ungauged watersheds for water, nutrients, and sediment.
- Compare regional water balances across Siberian, North American, and Northern European domains.
- Improve representation of permafrost in regional and global climate and hydrological models.
- Improve compatibility of *in situ* measurements, remotely sensed, and modeled data.
- Need for model intercomparison from local to pan-arctic scale.

Ocean Systems

Scientific Questions

- What was the timing and extent of the Eurasian ice sheet and its impact on the coasts and ocean?
- How do terrestrial ecosystem dynamics affect freshwater fluxes to oceans?
- What are the processes and effects of stamuhki: runoff over and under fast ice?

Data Issues

- Develop time series of sea level measurements around the Arctic Basin.
- Quantify biogeochemistry and primary productivity in estuaries and shelf regions.
- Document exchange in marginal seas, mixing and vertical fluxes associated with freshwater.
- Measurement of sea ice.
- Measurement of snow thermal, optical hydraulic properties.
- Develop improved methods for incorporating sediment-tracer studies in oceanographical studies depicting the fate of freshwater.

Modeling Issues

- Develop models of near-shore and estuarine exchanges of water and constituents.
- Further current understanding of the partitioning of freshwater into sea ice and sea water as a function of space and time.
- Develop fully coupled freshwater-sea ice-atmosphere simulations.

Atmospheric Systems

Scientific Questions

- What is the moisture flux convergence between Greenland and Scandinavia?
- What is the spatial and temporal variability of precipitation minus evaporation (P-E) over arctic land mass and ocean?
- Which factors control summer circulation regime near western Siberia?
- How does global warming forcing invoke feedbacks from the pan-arctic system and from the arctic water cycle?
- How does the atmospheric boundary layer respond to snow melt?

Data Issues

- Improve rawinsonde network in Eurasia and Canada.
- Secure agreements to work with numerical weather prediction modelers to jointly process pan-arctic data sets.

Modeling Issues

- Develop coupled, fully interactive arctic process models that include vegetation and how it interacts with the land surface and the atmosphere.
- Develop subgrid land surface process representations, with tests to determine which ones are important.
- Improve representation of permafrost in regional and global climate and hydrological models.

Human Systems

Key Issues

- Identify parameters, locations, and activities where we expect that human activities in the Arctic demonstrate most sensitivity to hydrological change.
- Conduct empirical studies of how observed hydrological variations affect human settlements and activities in the Arctic.
- Integrate findings from the two steps above with physical science results to project future human impacts of likely hydrological changes.

Appendix 3
Integration of Arctic-CHAMP with NSF and Other Federal Agency Initiatives

NSF Programs

Several offices of the Foundation support arctic research and there are numerous opportunities for Arctic-CHAMP to capitalize on this shared interest in the region. NSF has already invested heavily in field campaigns, modeling, monitoring and instrumentation, database development, and paleo studies.

NSF Field-Oriented Programs

Arctic-CHAMP intensive field campaigns will be based on a rich heritage drawn from the several ARCSS field programs listed in Box 6-2. Although many of these research efforts have been fundamentally interdisciplinary—for example, the collaborative work of boundary layer physicists and ecosystem field scientists at LAII sites—there has been little tangible movement toward an integration across all ARCSS Program elements.

Existing Synthesis Efforts

The ARCSS Synthesis, Integration and Modeling Studies (SIMS) program funds a small group of scientists who are beginning to work toward a quantitative picture of the Arctic as an interacting part of the earth system. At the heart of SIMS is a recognition of the importance of analysis of observational records as well as modeling as a means to catalyze cross-disciplinary understanding. Arctic-CHAMP would make an obvious contribution to the overall SIMS effort, and in some sense represents a substantial expansion of SIMS. The Arctic Natural Sciences Program provides core support to disciplinary studies in atmospheric sciences, earth sciences, ecosystem analysis, glaciology, and oceanography, as well as facilitation of cross-disciplinary polar projects supported by the NSF Office of Polar Programs (OPP). Coordination of Arctic-CHAMP with the Arctic Natural Sciences Program would be beneficial.

Role of Current NSF Paleo Studies

A seasonal-to-centuries time frame is targeted for Arctic-CHAMP which will require retrospective paleo, historical, and contemporary monitoring in tandem with models describing each of these time domains. There would be obvious connections to virtually all NSF-OPP initiatives. The Paleoenvironmental Arctic Sciences (PARCS) program helps to articulate the nature of Quaternary climates over the Arctic and sub-Arctic. PARCS itself has promoted synthesis studies including development of arctic proxy data (e.g., PARCS database) and data-model comparisons (e.g., Circum-Arctic PaleoEnvironments [CAPE], Paleoclimate Modeling Intercomparison Project [PMIP]).

NSF-Funded Monitoring and Instrumentation Efforts

OPP is active in supporting initiatives to improve the current state of the art and it is recommended that Arctic-CHAMP capitalize on progress to date. Two programs are noteworthy. The first, the Polar Instrumentation and Technology Development Program, supports research infrastructure in high-latitude environments, including development of novel techniques for harsh weather sampling. Second, the Long-Term Observatory (LTO) Program (joint between ARCSS, Division of Atmospheric Sciences, and Division of Environmental Biology) is currently supporting an array of individual projects seeking to establish arctic environmental observatories, sample repositories, and remote/ autonomous instrumentation. Long-term data sets associated with the NSF-LTER (Long-Term Ecosystem Research) Program also provide important supporting information. An integration and expansion of these NSF-supported environmental monitoring capabilities will be key to a successful Arctic-CHAMP.

Integrated Arctic Database Efforts

Another critical component of Arctic-CHAMP will be development of an integrated database of routinely collected observational data (e.g., precipitation, discharge), intensively sampled process-experiment results (e.g., from long-term watershed sites), biogeophysical forcing fields for Arctic-CHAMP models (e.g., from GCMs, weather prediction forecast/reanalysis models), and outputs from arctic system simulation models. A permanent archive for ARCSS-generated data is well established through the Arctic System Science Data Coordination Center at the National Snow and Ice Data Center (NSIDC). It is recommended that an ongoing dialogue be established with this data repository to accommodate Arctic-CHAMP data needs, with requisite funding support from ARCSS.

Interagency Issues and Opportunities

Arctic-CHAMP's Role in U.S. Arctic Research

Because Arctic-CHAMP is envisioned to catalyze arctic and earth system synthesis activities, it could make important contributions to federally funded programs beyond NSF. The Interagency Arctic Research Policy Committee (IARPC), a multioffice initiative chaired by NSF, could provide the appropriate multiagency context for Arctic-CHAMP. IARPC includes thirteen individual agencies and offices, setting priorities for future arctic research, preparing multiagency budget requests, and promoting cross-agency research coordination, including logistical planning and data sharing. With the Arctic Research Commission (USARC), it establishes integrated arctic research policy. Arctic-CHAMP provides an opportunity for IARPC to support its mandate of fostering integrated research and data exchange.

Arctic-CHAMP and SEARCH

Many of the issues described in this hydrology-related strategic plan are, in fact, interagency SEARCH issues. These are concerned with changes in arctic hydrology that may be related to the features of more broad-scale pan-arctic environmental change (see Box 4-1; Chapter 5 Boxes), and thus linked to the atmospheric and oceanic branches of the hydrological cycle (SEARCH SSC, 2001). In recognition of such linkages to the terrestrial domain, SEARCH evolved from ARCSS-OAII into a thematic program extending across several individual components of NSF-ARCSS. And now, SEARCH has become an interagency and international effort as well. In the U.S. it includes partners from NSF, NOAA, DOD, NASA, EPA, and DOI. Arctic-CHAMP, since it seeks to provide a long-term and pan-arctic perspective on the terrestrial water cycle, could play a prominent role in SEARCH and be NSF-ARCSS's contribution to the overall initiative.

Fostering Links to NOAA and Arctic Operational Analysis

The newly formed NOAA Arctic Research Office promotes studies into the role of the Arctic in global weather and climate variability, impacts of environmental change on marine resources, and vulnerability of human health in the Arctic to contaminant pollution. NOAA and NSF share leadership for U.S. interests in the Arctic Climate Impact Assessment (ACIA), a pan-arctic initiative of the intergovernmental Arctic Council set for completion in 2004. The NOAA National Center for Environmental Prediction (NCEP) also can provide contemporary numerical weather predictions, as well as systematic reanalysis of multiyear atmospheric dynamics to support diagnostic versions of Arctic-CHAMP models. The interaction should be two-way, with Arctic-CHAMP researchers working with NOAA staff to improve current versions of NCEP operational land surface schemes over high latitudes.

Arctic-CHAMP and NASA Satellite Missions

NASA has recently put forward a series of post-2002 mission concepts focused on land surface hydrology. These include the systematic collection of data on soil moisture, global precipitation, inland surface waters, and cold region processes (Jackson et al. 1999, Vörösmarty et al. 1999, Cline et al. 1999). The cryospheric monitoring mission, envisioned to include some combination of passive or active radiometers, will provide a pan-arctic view of freeze-thaw dynamics, critical information for activating and in-activating the large array of physical and biological processes considered by Arctic-CHAMP. NASA Earth Observing System (EOS) sensors will measure a very large number of biogeophysical variables (Parkinson et al. 2000), which should also be exploited by Arctic-CHAMP diagnostic models of the contemporary pan-Arctic. The Global Precipitation Mission (GPM) could be enhanced by the use of Arctic-CHAMP validation products over the pan-Arctic. Work should be directed within Arctic-CHAMP to develop a means for assimilating the operational data sets to emerge from these missions.

Glacial mass balance and the associated discharges of meltwater is an important observational requirement within Arctic-CHAMP. GLIMS (Global Land Ice Measurements from Space) is analyzing the world's glaciers using data from EOS-ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). NASA ICESat, scheduled to launch in July 2001, is a benchmark EOS mission to measure ice sheet mass balance, cloud and aerosol heights, vegetation, and land topography via laser altimetry. NASA's Program in Arctic Regional Climate Assessment (PARCA) is currently using airborne laser altimetry to measure ice sheet thickness changes, with an emphasis on the changing character of the Greenland ice sheet.

Appendix 4
International Collaborations

There are several major international science initiatives—both ongoing and planned—that focus on the Arctic. Many have made substantial investments in polar research and could provide a mutually beneficial synergy with Arctic-CHAMP.

Among the numerous ongoing efforts, two broad-scale scientific initiatives would provide benefit to Arctic-CHAMP. The World Meteorological Organization's World Climate Research Program and the International Geosphere-Biosphere Program (IGBP) represent major efforts at securing an improved understanding of the interactions across atmosphere-land-ocean system and their impacts on climate dynamics and the biosphere. The pan-Arctic, as a well-bounded, linked land-atmosphere-ocean system, provides a unique test bed for regional and global climate, biology, and biogeochemical feedback studies. The World Climate Research Program (WCRP) Global Energy and Water Experiment (GEWEX) and its focus on improving land-atmosphere linkage modeling has numerous activities, including large-scale river basin experiments, such as in Siberia, that will aid in the integration of water cycle dynamics into future climate models. WCRP's Arctic Climate System Study (ACSYS) and follow-on Climate and the Cryosphere (CliC) Project provides another important programmatic link (WCRP 1998, 1999, Allison et al. 2000). Major synthesis efforts are underway in the IGBP, including analysis of paleoenvironmental dynamics across the high north. SEARCH has already integrated some of its activities with the WCRP Climate Variability and Predictability Study (CLIVAR) and provides an excellent vehicle by which to unite Arctic-CHAMP hydrology with a much larger international initiative.

Intercomparison Studies

An important component of Arctic-CHAMP is the objective assessment of algorithms and observational data sets, and there are several opportunities for linkages to ongoing intercomparison experiments. Intercomparison studies of the type envisioned for Arctic-CHAMP are already ongoing in several international fora (Box 6-3) (e.g., Goodison et al. 1998). These treat land-surface exchanges including the dynamics of vegetation and snow and consider both contemporary and paleo time domains.

Existing Field Sites

A central idea behind Arctic-CHAMP is to create a series of well-instrumented process study sites across the northern high latitudes. The program could benefit greatly by conjunctive use of existing study sites, supported by both federal and international science agencies (Box 6-3). The value of such experiments is highly evident, with the corresponding data sets typically analyzed for several years after the dedicated field experiments have ended (e.g., BOREAS). Sustaining long-term experiments will provide even more scientific value. Cost-sharing across several international agencies will be required but will provide to all the observational context by which to monitor ongoing arctic change and improve upon our current level of process understanding.

Remote Sensing

The use of remote sensing will be essential for achieving a truly pan-arctic perspective (Goodison et al. 1999). U.S.-based activities, discussed in chapter 2, are well-augmented by several international efforts. The utility of radar systems to infer water and freeze or thaw state, together with the absence of a U.S. radar satellite system, makes collaboration with European, Japanese, and Canadian space agencies essential. Such data have traditionally been costly both in terms of their price and computer storage and processing requirements, making it difficult to assemble long and coherent time series. A funding commitment to make these data sets available would help to achieve a more complete picture of the seasonal storage and release of frozen water than is currently possible.

Major Monitoring Programs

Several multiorganizational observational frameworks for systematic change detection and improved climate prediction are also in place, exemplified by the Global Climate and Global Terrestrial Observing Systems (GCOS/GTOS). These seek to establish a global reference network of land surface observational weather/climate stations, including several of high relevance to the pan-Arctic (Cihlar et al. 2000). These activities also encompass International Permafrost Association activities in monitoring frozen soil condition. The immediate challenge is for individual countries to acquire the resources to implement an observational program that will meet both their own needs and contribute to those outlined for GCOS/GTOS networks. Canada, for example, plans to enhance its current GCOS surface network and its cryospheric observing system in remote northern regions as its contribution to international arctic science.

Numerical Weather Prediction and Reanalysis

The Arctic-CHAMP models will be cast in both a diagnostic and prognostic mode. Important data sets are currently being prepared by the European Center for Medium-range Weather Forecasting (ECMWF). The forthcoming ERA-40 global reanalysis will provide a nearly half-century time series (1957–present) of atmospheric variables at high spatial and temporal resolution. It is critical to assess the performance of this and other such products from the standpoint of water and energy conservation and the production of sensible predictions with respect to the land surface hydrological cycle. ECMWF has been receptive to the inputs of Arctic researchers and a productive interaction could be further promoted through Arctic-CHAMP.

International Data Archives

Arctic-CHAMP data requirements could take advantage of several major international data collection, archiving, and distribution activities. These involve both global and arctic-wide data repositories. Given the wealth of geophysical data sets currently available, meta-data systems and search engines optimized for Arctic-CHAMP research needs should be established. An early activity of the Arctic-CHAMP Synthesis and Education Center could be the assembly of existing, hydrologically relevant arctic environmental data to provide a quantitative benchmark for assessing future change.