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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With contributions from scientists at the NSF-ARCSS Hydrology Workshop, Santa Barbara, CA, September 2000

Cover photo: Aerial view of Accomplishment Creek and the Sagavanirktok River in the Brooks Range of Alaska. Photo by D. L. Kane.

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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-*

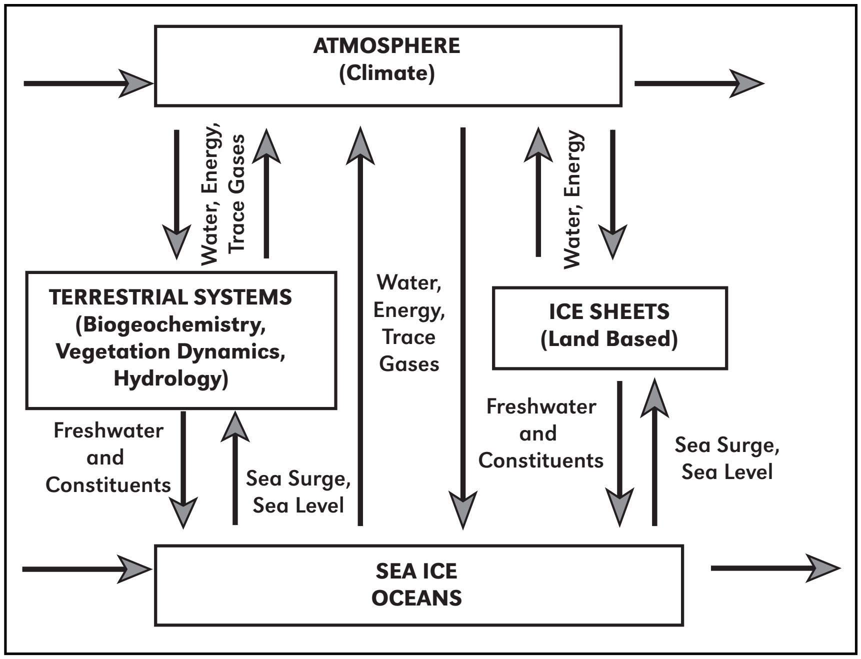

Figure 1-1. Conceptual diagram of the arctic system, showing linkages among the atmosphere, land surface, and ocean systems. Links within the arctic region as well as the larger earth system must be considered to achieve an integrated view of the hydrological cycle (from Walsh et al. 2001).

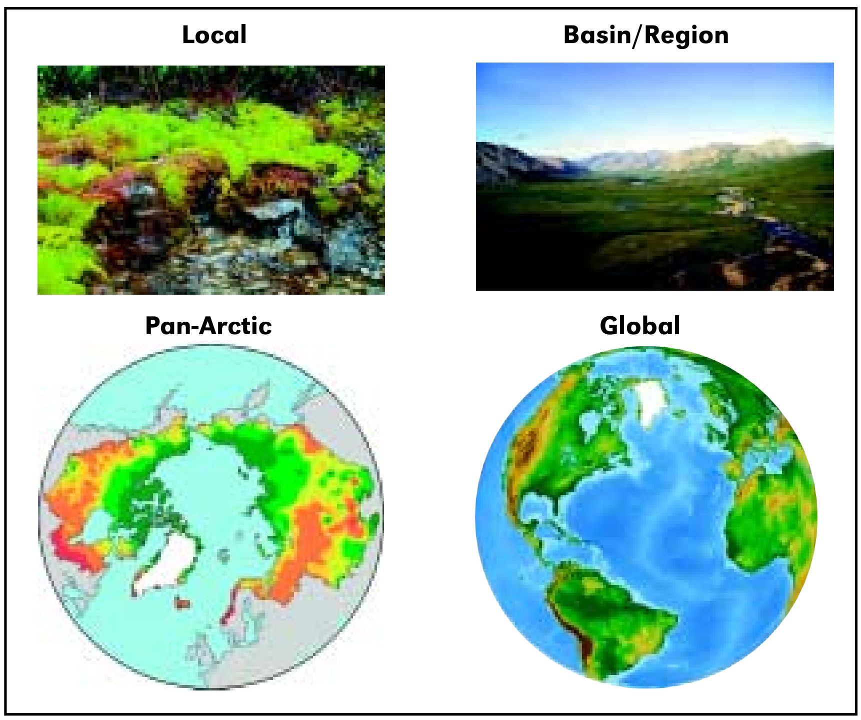

Figure 1-2. Multiscale approach toward achieving synthesis of pan-arctic hydrological dynamics and identifying its role in the larger earth system. Information from all scales is necessary to ensure mutual consistency of predictive models. Biophysical, biogeochemical, and human dimension issues should 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

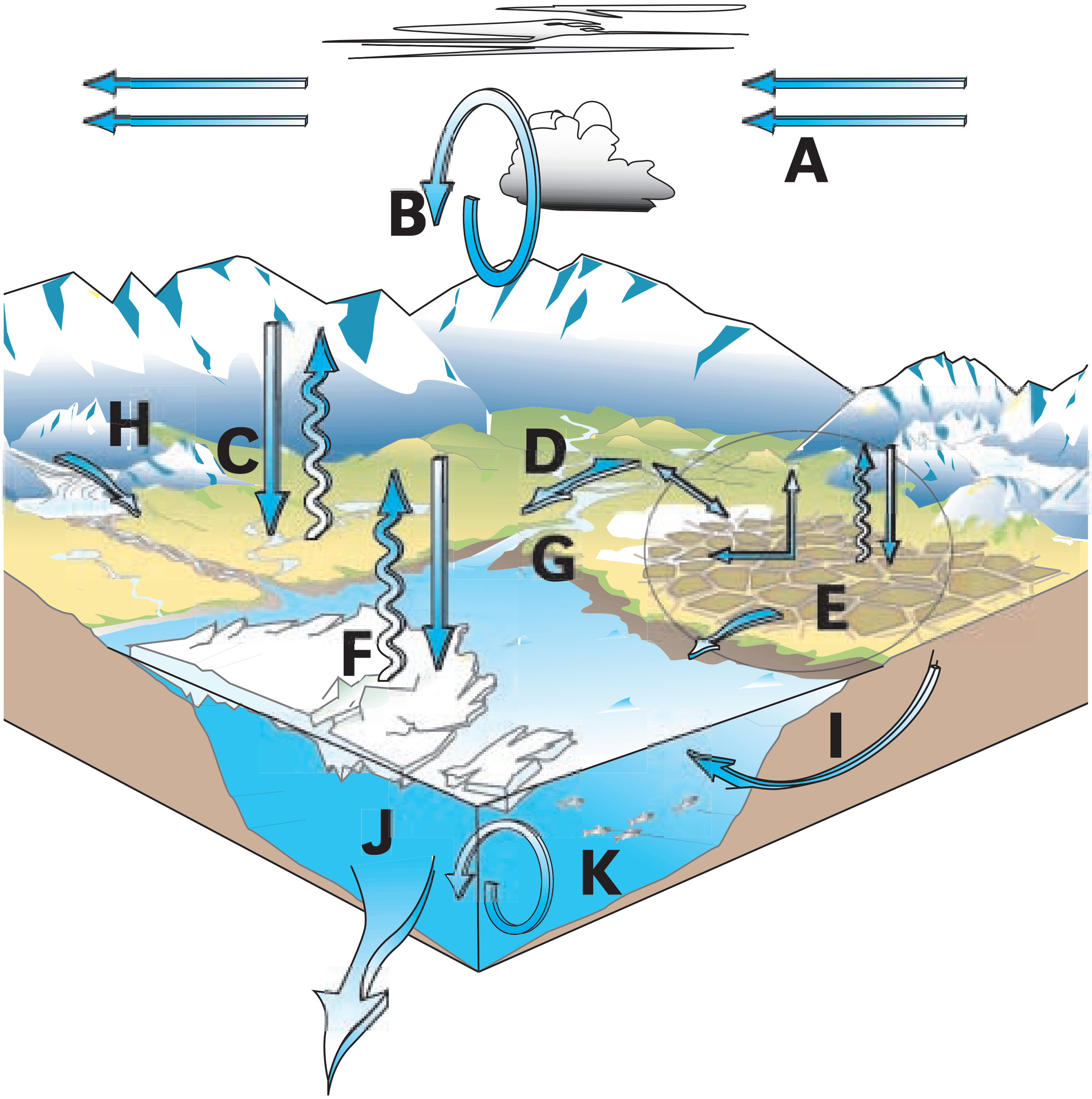

Figure 1-3. Conceptual model of the arctic hydrological cycle, with key linkages among land, ocean, and atmosphere. The coupling of these components within the Arctic and to the larger earth system remains an important yet unresolved research issue. The hydrological cycle is inextricably connected to 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.

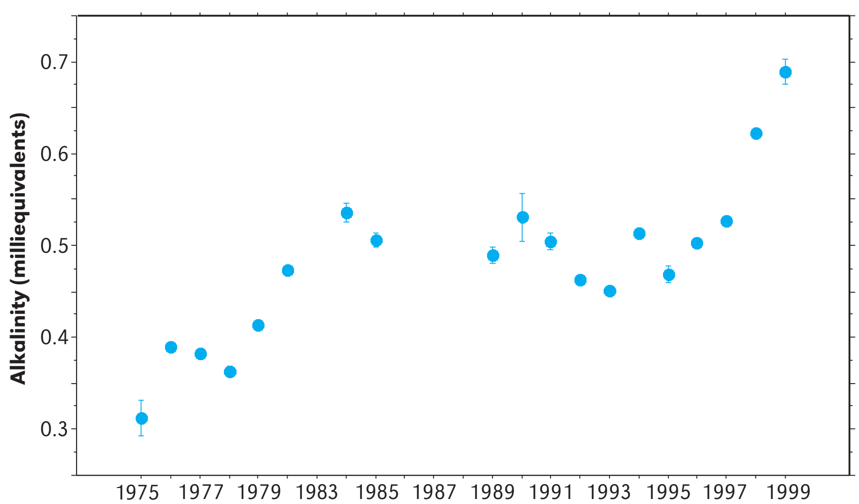

Figure 1-4. Progressive change in alkalinity of Toolik Lake, Alaska, from long-term, synergistic hydrology and hydrochemical measurements. Chemical changes may signal the warming of permafrost in response to global climate change (Neil Bettez, Arctic LTER database).