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Arctic–CHAMP: A program to study Arctic hydrology and its role in global change

Charles J. Vorosmarty
charles.vorosmarty@unh.edu

Larry Hinzman

Bruce Peterson

David Bromwhich

Lawrence C. Hamilton
University of New Hampshire, Durham, lawrence.hamilton@unh.edu

See next page for additional authors

Comments

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Authors

Charles J. Vorosmarty, Larry Hinzman, Bruce Peterson, David Bromwhich, Lawrence C. Hamilton, James Morison, Vladimir Romanovsky, Matthew Sturm, and Robert Webb

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Arctic-CHAMP: A Program to Study Arctic Hydrology and its Role in Global Change

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The Arctic constitutes a unique and important environment that is central to the dynamics and evolution of the Earth system. The Arctic water cycle, which controls countless physical, chemical, and biotic processes, is also unique and important. These processes, in turn, regulate the climate, habitat, and natural resources that are of great importance to both native and industrial societies. Comprehensive understanding of water cycling across the Arctic and its linkage to global biogeophysical dynamics is a scientific as well as strategic policy imperative.

The Arctic is inherently a dynamic system with rapid shifts in state demonstrated repeatedly in the paleo record [*Overpeck et al.*, 1997]. Yet, there is mounting evidence that it is now experiencing an unprecedented degree of environmental change—broad-scale increases in air temperature, thinning of sea ice, melting of glaciers, thawing of permafrost, and reductions in snow cover [*Serreze et al.*, 2000; *SEARCH SSC*, 2001]. Periodic failure of important fish landings and its economic consequences are linked to low salinity anomalies, and thus, to changes in the freshwater cycle [*Hamilton and Allanson*, 2001]. There is also concern about how recently-observed increases in freshwater supply to the Arctic Ocean [e.g., *Semiletov et al.*, 2000] could reduce thermohaline circulation, with potentially enormous global-scale consequences [*Broecker*, 1997]. Unfortunately, the sources and ultimate consequences of these many changes are still poorly understood.

In September 2000, a workshop supported by the National Science Foundation's Arctic System Science (NSF-ARCSS) Program was convened at the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, California. The workshop participants assessed the current state-of-the-art in Arctic systems hydrology and identified research priorities for achieving predictive understanding of feedbacks arising from changes to the Arctic water cycle. The meeting was well-represented within the Arctic research community, with more than 30 participants drawn from the disciplines of land surface hydrology, terrestrial

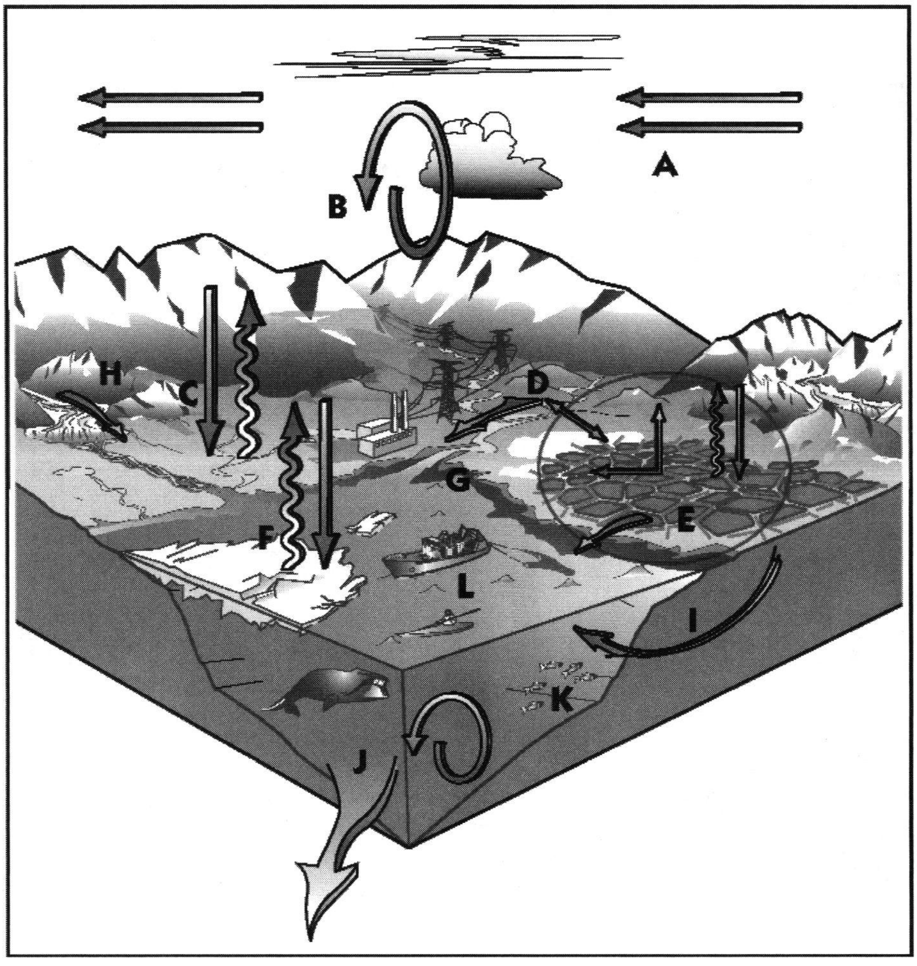

Fig. 1. This view of the Arctic hydrological cycle shows key linkages among land, ocean, and atmosphere. Quantifying the coupling of these components within the Arctic and to the larger Earth system remains an important yet unresolved research issue. The hydrological cycle is inextricably connected to 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 the pan-Arctic region. 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 = water cycling and runoff over 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; L = socio-economic factors. Original color image appears at the back of this volume.

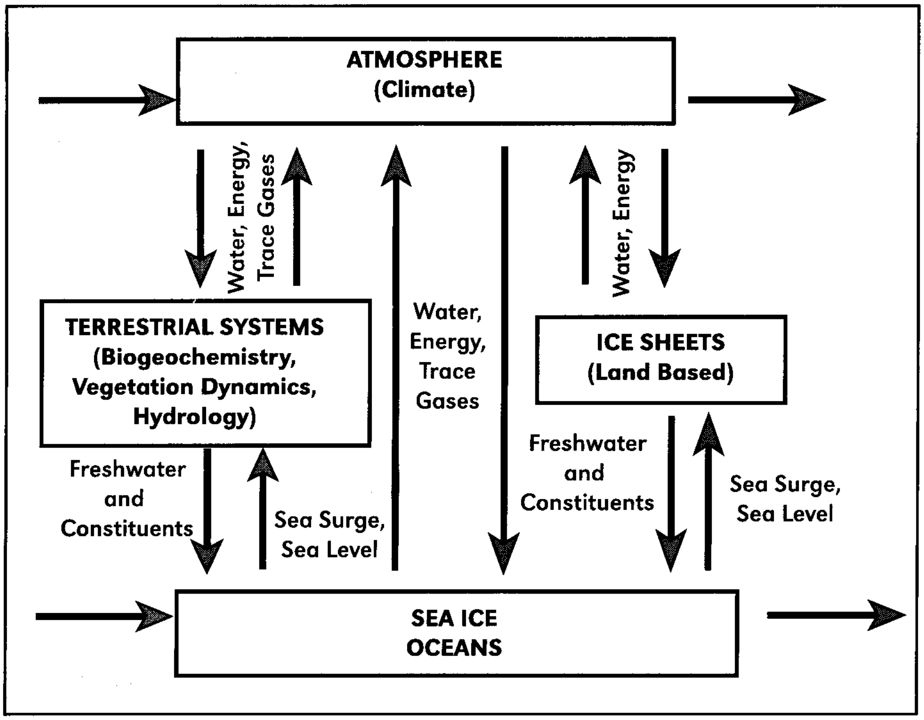

Fig. 2. A conceptual diagram of the Arctic system will show linkages among the atmosphere, land surface, and ocean components. Links within the Arctic region as well as the broader Earth system must be considered to achieve an integrated view of the hydrological cycle (from Walsh et al. [2001]).

and freshwater ecology, atmospheric dynamics, oceanography, socioeconomics, simulation modeling, remote sensing, and geo-spatial analysis.

A drafting committee captured the deliberations and reported its findings in a peer-reviewed strategy document [*Vörösmarty et al.*, 2001] that highlights the scientific, technical, and institutional challenges that separate us from a clear understanding of Arctic hydrological change. It also presents a plan for new synthesis research to clarify the importance of Arctic fresh water within the Earth system and in global change. This article provides a brief overview of key elements in the report and discusses its call for the creation of a major new research program at NSF—Arctic-CHAMP, the pan-Arctic Community-wide Hydrological Analysis and Monitoring Program.

Arctic Water Cycle as an Integrating Framework

The hydrologic cycle is intimately connected to all major processes that define the character of the Arctic system as a whole (Figure 1). Through seasonal storage of snow and ice, open water, and sea-ice cover, the Arctic water cycle helps to regulate the planetary heat balance and to define circulation in the global oceans. Water status in terrestrial ecosystems controls the emission of radiatively important trace gases and alternatively may help to sequester atmospheric CO_2. Arctic rivers discharge fresh water, which helps to control the timing and distribution of sea ice and nutrients that support ocean productivity. Furthermore, Arctic ecosystems, highly dependent on the state and availability of water, provide forestry and fisheries products that are important both locally and in the global marketplace. Through its central role in the biogeophysics of the Arctic, the hydrologic cycle provides an ideal organizing framework for system-wide synthesis.

The Arctic domain may also 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 (Figure 2). It is the most "closed" and land-dominated of all the major ocean basins. The Arctic Ocean's main connection to the global ocean system is through two relatively well-defined exchanges through the Bering Strait and Nordic Seas. Sea ice generated in the Arctic Ocean can be tracked on its way southward to the Atlantic. Arctic circumpolar circulation, including the Polar Front, is a fundamental feature of the Earth's atmospheric system that can be fairly well-identified and across which moisture and energy fluxes can be tracked. Relative to other parts of the world, the domain is arguably pristine, and thus an excellent "laboratory" for isolating the impact of natural variability from that associated with anthropogenic change. A pan-Arctic perspective, encompassing the entire landmass contributing runoff to the Arctic Ocean, as well as the surrounding air-shed, will be necessary for identifying the unique contributions to observed environmental change due to nature versus human activity.

Current State-of-the-Art

Knowledge of Arctic hydrology remains incomplete due, in part, to the traditions of disciplinary science. Recent activities supported by NSF-ARCSS have clearly identified the importance of the terrestrial water cycle; this is reflected most notably in the Land-Atmosphere-Ice Interactions component of the larger NSF-ARCSS program for Action (1997) (or LAII), Modeling the Arctic System (1997), Toward an Arctic System Synthesis (1998), Toward Prediction of the Arctic System (1998), and Draft LAII Science Plan (2001) workshop reports and steering documents. Although these reports recognized the key role of water, a coherent framework through which to study Arctic hydrology per se never materialized.

To be sure, excellent and groundbreaking Arctic science has emerged, with much of it funded by the NSF Office of Polar Programs. A broad and growing disciplinary literature exists from which to draw a quantitative summary of some of the major pools of water

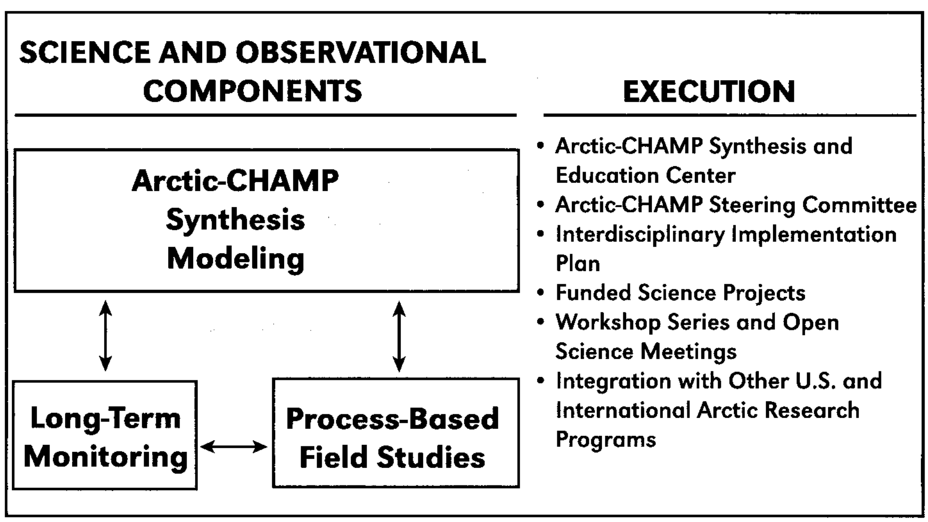

Fig. 3. The overall framework of the pan-Arctic Community-Wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) involves a close interaction among its major long-term observational, experimental, and simulation components.

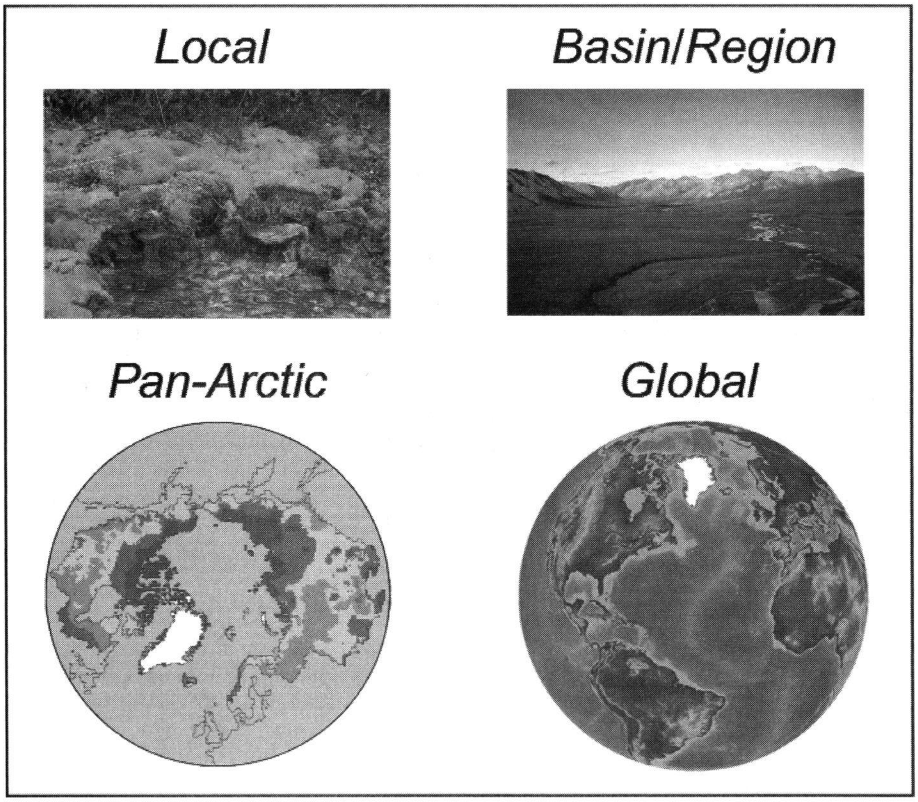

Fig. 4. Achieving synthesis of pan-Arctic hydrological dynamics and identifying its role in the Earth system requires a multi-scale approach. Information from all scales is necessary to ensure mutual consistency among predictive models. Biophysical, biogeochemical, and human dimension issues should be simultaneously addressed. (Lower left panel shows precipitation over the landmass that can potentially supply fresh water to the Arctic Ocean.) Original color image appears at the back of this volume.

and energy found in the Arctic atmosphere, soils, rivers, lakes, glaciers, sea ice, and ocean waters. Estimates of the energy and water transport into and out of the Arctic are also becoming available. While providing a useful backdrop, this body of currently available research is hardly comprehensive and is difficult to interpret from a systems point of view.

Major Scientific Challenges

The stocks, fluxes, and phase changes of water can be found throughout all major domains of the Arctic system (Figure 2), thus making hydrology central to our understanding of the Arctic and Arctic environmental change. The NSF-ARCSS Hydrology Workshop Steering Committee challenged the workshop participants with the following question: 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?

A consensus view from the workshop, later articulated in the subsequent report to NSF, indicated that the answer is *no*. We specifically lack the synthesis-oriented research needed for a comprehensive understanding of how changes to the Arctic water cycle will reverberate within the Arctic system as a whole, and, through physical, chemical, and biotic teleconnections, the Earth system. Three major obstacles have hindered progress toward synthesis. The observational network for routine monitoring is sparse and in many cases in decline. There is also an absence of integrated data sets of spatially and temporally harmonized biogeophysical information over the pan-Arctic domain. Second, there are numerous gaps in our current understanding of basic scientific principles and processes with respect to water cycling in Arctic environments. Finally, there is a lack of cross-disciplinary synthesis research and modeling for deciphering feedbacks on the Earth system and on society arising from Arctic hydrological change.

Any assessment of contemporary and potential future states of the Arctic system must rely on knowledge of the changing state of key hydrological variables and how feedbacks emerge in response to environmental change. This knowledge, in turn, depends on high-quality, quantitative information. The absence of the necessary hydrological information limits our ability to formulate testable hypotheses. Even with improvements in the quality and availability of some data sets, such as from remote sensing, there are limited opportunities for integrative study due to the lack of instrumented field sites, scientific infrastructure, and sustained funding. These barriers to synthesis exist across the spectrum of spatial scales, from local to regional to global, all of which will be necessary for understanding the full dimension of Arctic hydrological change. Sound policies for environmental protection await resolution of these scientific and technical challenges.

New Synthesis Effort Required

The gaps identified above demonstrate an urgent need to reformulate the manner in which Arctic water cycle research is funded and executed. A dedicated federal research program to support Arctic hydrological synthesis is urgently needed. This synthesis would be based on the integration of process-based understanding, observation, and simulation of full-system linkages. Though such a program does not yet exist, it has been called for many times; for example, in the recent U.S. Global Change Research Program's initiative on the water cycle [*USGCRP Water Cycle Study Group*, 2001].

To support new science, our committee's central recommendation is that NSF invest in the development of a pan-Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP) to provide a framework for synthesis studies of the pan-Arctic water cycle and to articulate the role of fresh water in terrestrial ecosystem, biogeochemical, biogeophysical, ocean, climate, and human dynamics. The primary aim of Arctic-CHAMP would be to catalyze and coordinate interdisciplinary research, with the aim 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:

- Assess and better understand the stocks and fluxes that constitute the Arctic hydrologic cycle.
- Document natural variability in and changes to the Arctic water cycle, contributing a hydrological component to the multi-agency Study of Environmental ARctic Change (SEARCH) Program.
- Understand the sources of natural variability and causes of Arctic water cycle change and assess their direct impacts on biological and biogeochemical systems.
- Develop predictive simulations of the response of the Earth system and human society to feedbacks arising from natural variability and progressive changes to Arctic hydrological systems.

Elements of the Research Program

The overall structure of Arctic-CHAMP is shown conceptually in Figure 3. It consists of three interacting components: (a) compilation and evaluation of long-term monitoring of the hydrologic cycle; (b) field observations and focused process studies; and (c) simulation models operating over multiple time and space domains. The scaling of local to regional to pan-Arctic dynamics using advanced data analysis, GIS, and modeling should be a key focus of the effort (Figure 4). The goal of achieving pan-Arctic synthesis makes newly emerging remote sensing capabilities [e.g., *Running et al.*, 1999; *Walsh et al.*, 2001] especially promising in this context.

Table 1. Examples of the coordinated set of measurements that should be made at an Arctic-CHAMP process study site. Expanding the current network of field sites and the number of variables routinely observed is an urgent research need.

Hydrological and Other Geophysical Measurements
- Precipitation Amount (Year-round)
- Air Temperature
- Evapotranspiration and Sublimation
- Solar Flux and Surface Energy Balance 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 (frozen and thawed)
- Runoff Flow Paths
- Stream and Large River Discharge
- Sediment Flux
- 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

Long-term Observations. The value of documenting long-term changes in Arctic temperature, precipitation, snow cover, sea ice, and storms has been demonstrated [*Serreze et al.*, 2000]. Progressive changes are occurring across the very region where general circulation models (GCMs) have predicted the earliest and largest greenhouse warming [*Houghton et al.*, 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.*, 2002].

We recommend that steps be taken immediately to reconstitute, sustain, and improve on the basic hydrologic monitoring systems of the Arctic to provide the long-term observations needed to understand the consequences of global change on the hydrosphere. A sustained commitment of resources is required to develop the necessary infrastructure and data distribution systems.

Arctic-CHAMP support for observational networks should include data rescue, augmentation of existing networks, and improvement of automated instrumentation in harsh environments. Integrated data sets that are error-checked, of consistent spatial and temporal coverage, and mass- and energy-conserving are urgently needed.

Field-based Process Studies. In response to the conspicuous lack of fully coordinated studies in Arctic hydrology, we recommend that a commitment be made to establish a core set of watershed study sites across the pan-Arctic. At these sites, a tightly linked set of process-based measurements should be systematically executed over the long-time horizon of years to decades. An interdisciplinary perspective is central to the success of this fieldwork. Table 1 summarizes the set of integrated measurements that should be made. To fill current gaps in our process-based knowledge, to characterize natural variability, and to improve our capacity to predict Arctic hydrologic and ecosystem change, research at these sites should include experiments to uncover hydrologic mechanisms through both fieldwork and modeling; measurements to facilitate comparative analysis across 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 should constitute the collection of hydrological as well as biogeochemical and biological measurements, including seldom-made winter observations.

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 refinement, hypothesis generation, and pan-Arctic application. ARC-ISM will also provide a framework for integrating the long-term observations and process-based experiments of Arctic-CHAMP. ARC-ISM is anticipated to be cast as an Earth system model focused on the pan-Arctic and treating the specific elements shown in Figures 1 and 2.

Newly-developed Arctic regional climate models that incorporate several interacting components of the hydrologic system [e.g., *Lynch et al.*, 2001] thus provide an important precedent for an ARC-ISM. The simulation should treat the Arctic's climate, land surface hydrology, ocean, vegetation, biogeochemical, and human systems in an integrated fashion. Equally 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 natural variability and global change. Retrospective, contemporary, and future time frames need to be analyzed, with ARC-ISM cast as a diagnostic, as well as a prognostic modeling tool.

Implementation of Arctic-CHAMP

While each element of Arctic-CHAMP is important in its own right, integration will be the key to significant and rapid progress. To this end, Arctic-CHAMP should be structured to provide facilities and synthesis support activities linking the three components of the proposed program—monitoring, process studies, and synthesis modeling. To execute this effort, we make the following specific recommendations:

- Establish the Arctic-CHAMP Synthesis and Education Center (CSEC) to serve as the physical location for several of the scientific activities of the program. Center activities should be cast to coordinate the modeling, field research, and monitoring components of CHAMP.
- Create an Arctic-CHAMP Scientific Steering Committee (AC-SSC) to formulate a detailed Interdisciplinary Implementation Plan and then coordinate execution of the Program.
- Establish a set of interdisciplinary process-based catchment study sites.
- Select a core group of Arctic-CHAMP researchers through peer review. The research team would include principal investigators and their postdoctoral fellows and graduate students, many in residence at CSEC. The team would have representatives from the biogeophysical and socioeconomic realms and include both observationalists and modelers.
- Convene an ongoing Arctic-CHAMP workshop series and open science meetings to sustain fresh input from the Arctic and Earth system science research communities.
- Foster maximum synergy among NSF and other U.S. agency programs using the hydrologic cycle studies of Arctic-CHAMP as the NSF-ARCSS contribution to the multi-agency SEARCH Program and to support NSF Biocomplexity, Information Technology, public outreach, and education programs. Maximum use should be made of operational, pan Arctic data sets from the National Aeronautic and Space Administration and the National Oceanographic and Atmospheric Administration.
- Create and sustain a vigorous set of international science and monitoring partnerships.

This last point deserves special attention, as most of the pan-Arctic landmass resides in

Table 2. Points of contact, and areas of needed research, where a rapidly changing physical environment is likely to affect human activities across the Arctic. There are, in addition, the broader-scale implications of a changing Arctic on planetary heat balance, climate dynamics, and ocean circulation which would affect a much larger segment of human society.

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 & ice-road degradation	Tourism	Changes in species & 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 & fishing	Shipping transport	Commercial fisheries	Subsistence hunting	Contaminant
Contaminants	Water supply/ treatment	Spill prevention remediation	Commercial fisheries	Subsistence hunting & fishing	Human exposure

Russia and Canada. No single NSF program, or even the U.S. Arctic research community as a whole, could achieve the degree of synthesis required. This committee informally identified more than 40 ongoing international Arctic science programs, inter-comparison studies, field and process experiments, remote sensing programs, monitoring and assessment campaigns, numerical weather prediction studies and re-analyses, data archives, and United Nations framework convention activities that deal with the Arctic. NSF must forge strategic international partnerships to be successful in the Arctic-CHAMP endeavor. Active coordination will be of obvious help in maximizing synergy and avoiding duplication of effort.

Policy Implications

Scientists have yet to observe and understand the full scope of pan-Arctic variability and progressive change, but at the same time, they are under increasing pressure to advise policy-makers as they struggle with how best to manage rapid contemporary and future global change. We see great value in pursuing interdisciplinary and synthetic research, driven not only by scientific curiosity, but as well, by the needs of the policy community. Response strategies to climate change transcend the domains of traditional disciplines [*U.S. National Assessment*, 2000], thus making the interdisciplinary approach embodied in Arctic-CHAMP highly responsive to this emerging policy requirement.

The contributions of an Arctic-CHAMP toward articulating the diverse physical, biological, and human vulnerabilities to natural variability and progressive global change are intended to provide an important impetus for international cooperation in wisely managing this critical part of the Earth system. The potential impact of Arctic system change on society is impressive in its scope (Table 2). Given the central role of the Arctic and its freshwater cycle in the Earth system, the impact of regional environmental 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.

A copy of the full report to NSF can be obtained from the Arctic Research Consortium of the United States (ARCUS), 3535 College Rd., Suite 101, Fairbanks, Alaska 99709-3710 USA; E-mail: arcus@arcus.org, or downloaded at http://www.arcus.org/ARCSS/hydro/.

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Authors

Charles Vörösmarty, Larry Hinzman, Bruce Peterson, David Bromwich, Lawrence Hamilton, James Morison, Vladimir Romanovsky, Matthew Sturm, and *Robert Webb*

For additional information, contact Charles Vörösmarty, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, USA; E-mail: charles.vorosmarty@unh.edu.

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Satellite Imagery Proves Essential for Monitoring Erupting Aleutian Volcano

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Mt. Cleveland is one of more than 40 active volcanoes in Alaska that is monitored by the Alaska Volcano Observatory (AVO). It is located on the western half of Chuginadak, a remote and uninhabited island in the east central Aleutians that lies 1526 km southwest of Anchorage. The closest inhabited community, Nikolski, is 75 km to the east on Umnak Island (Figure 1).

Mt. Cleveland erupted explosively on 19 February and on 11 and 19 March 2001. Because the volcano is not yet monitored with seismic, deformation, or other geophysical instruments, satellite imagery was the only effective tool for detecting and monitoring this activity. Eruption clouds and elevated surface temperatures were detected on multiple satellite data sets. The largest eruption was in February. This first eruption cloud and the subsequent wave of ash (Figure 1) that drifted across Alaska extended up to flight levels and prompted cancellation and re-routing of air traffic throughout the North Pacific region on 19 and 20 February.

AVO made observations during and after these three eruptions using National Oceanic and Atmospheric Administration (NOAA) satellite data that permitted effective monitoring and hazard mitigation, despite the fact that ground-based geophysical instruments were not available. The Mt. Cleveland event provides an important case study of eruption detection and plume tracking methods, characterization of the ash cloud, and weather pattern effects at a remote location.

Satellite Monitoring

Volcanoes in Alaska are monitored in real or near real-time using satellite [*Schneider et al.*, 2000; *Dean et al.*, 1998] or seismic techniques. Often, observers on the ground and pilots report anomalous activity. In the Alaska region, approximately half of the volcanoes are monitored using seismic techniques, and all surface temperatures and airborne plumes are monitored using satellite techniques.

Satellite systems routinely used by AVO for daily, real-time monitoring include the NOAA Advanced Very High Resolution Radiometer (AVHRR) and the Geostationary Operational Environmental Satellite (GOES). Both of these data sets include visible and thermal infrared wavelength images. AVHRR data, recorded from a polar orbiting satellite, has a 1.1-km spatial resolution at nadir. AVHRR records approximately 10 images of any one volcano every 24 hours due to overlapping data from successive orbits at high latitudes. These images are not collected at regular intervals, but instead tend to come in two batches a day over several hours. The frequency of coverage decreases for regions well to the east and west of the receiving station at Fairbanks.

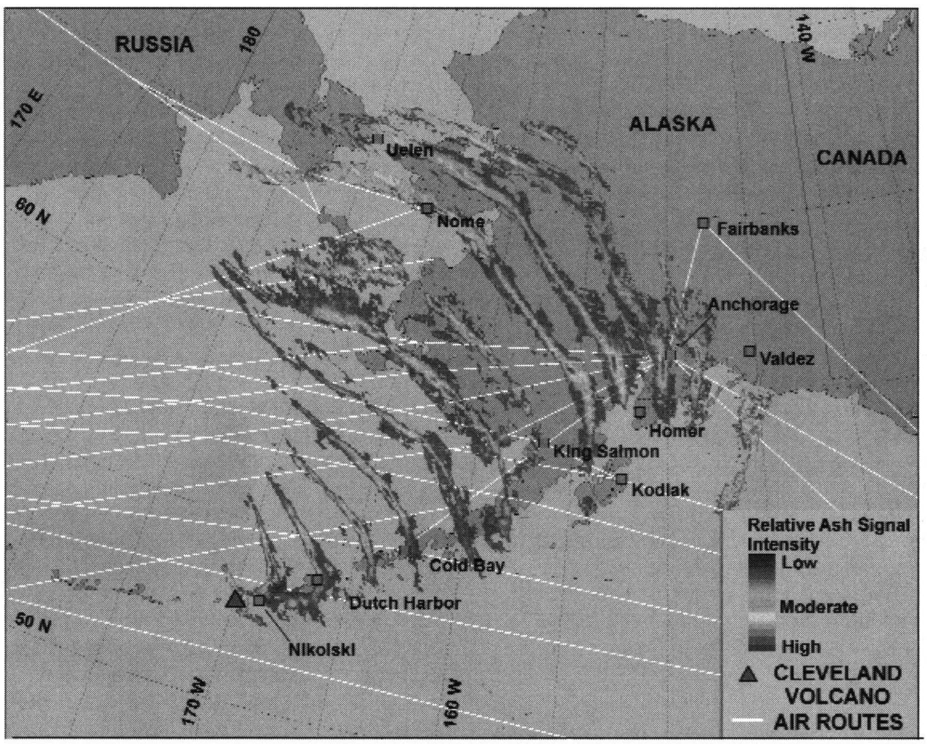
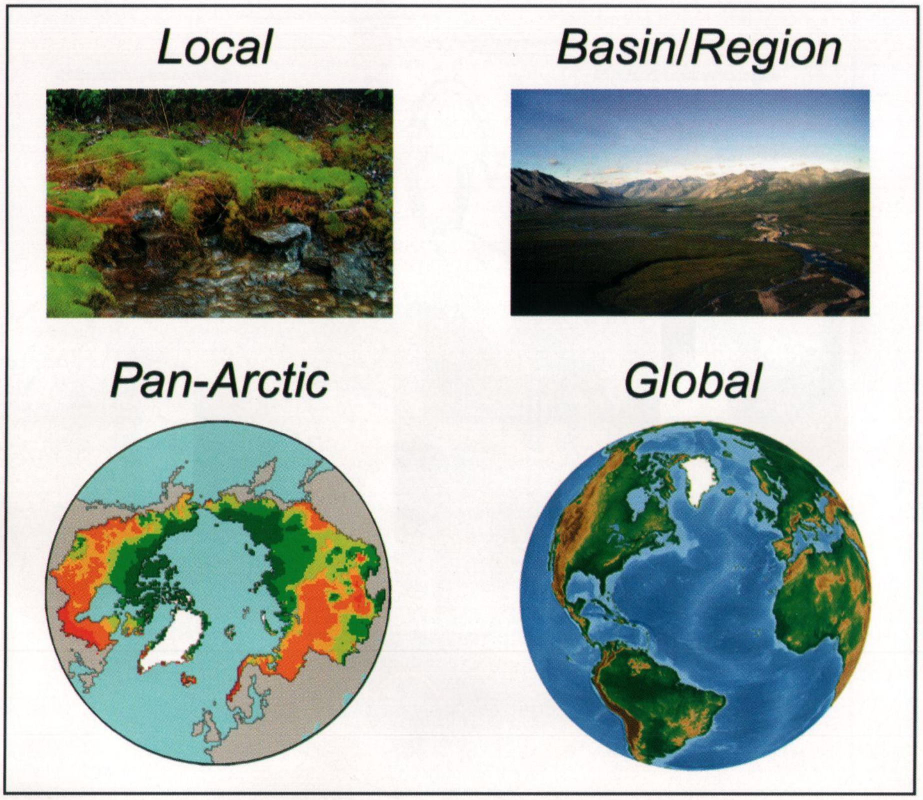


Fig. 1. This time-sequential satellite image shows the position of the eruption cloud from Mt. Cleveland over a 3-day period, 19-21 February 2001. Each ash cloud was observed on a single GOES-10 satellite image recorded at a single time step. Thirteen images recorded at consecutive time steps using the split-window technique were used to form this composite. The first image, 1615 UTC on 19/2/01, was taken approximately 2 hours after the initial eruption start time. Image noise has been removed for clarity. (Image created by K. Papp.) Original color image appears at the back of this volume.



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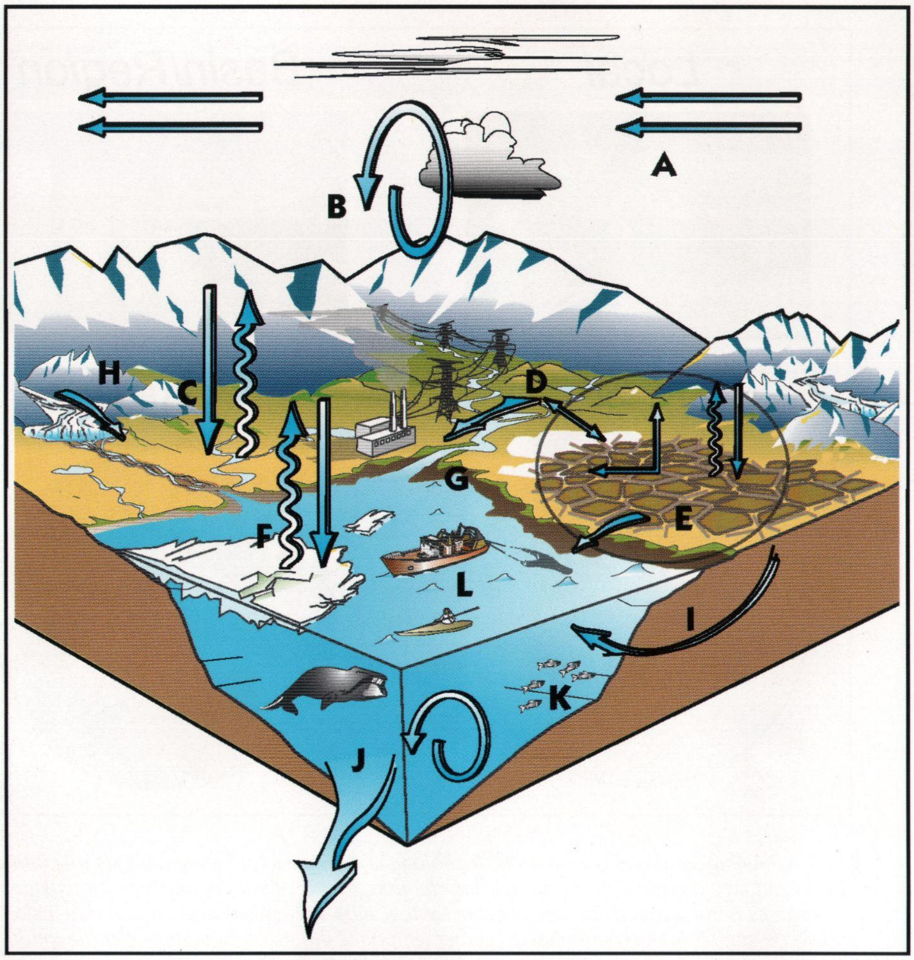

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Fig. 1. This view of the Arctic hydrological cycle shows key linkages among land, ocean, and atmosphere. Quantifying the coupling of these components within the Arctic and to the larger Earth system remains an important yet unresolved research issue. 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 the pan-Arctic region. 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 = water cycling and runoff over 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; L = socio-economic factors.